Preparing The Heart for Duty: Virtual Reality Biofeedback in an Arousing Action Game Improves in-action Voluntary Heart Rate Variability Control in Experienced Police

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***Abstract*—Adequate control over evolutionary engrained bodily stress reactions is essential to avoid disproportionate responses during highly arousing situations in police. This regulation can be trained via heart rate variability (HRV)-biofeedback, a widely used intervention aiming to improve stress regulation, but typically conducted under passive, low arousing conditions. We integrated closed-loop HRV-biofeedback in a newly designed engaging Virtual Reality (VR) action game containing the behavioral elements typically compromised under stress. Specifically, we aimed to train in-action physiological self-control under high arousal to allow improved transfer to real-life. A pre-registered (*https://osf.io/cdsbx*) quasi-randomized controlled trial in 109 police trainers demonstrated highly significant increases in HRV (32% average), through the engaging and gamified closed loop biofeedback. This ability to voluntarily upregulate in-action HRV transferred to game sessions without biofeedback (near transfer). Critically, we could additionally demonstrate transfer to a professional shooting performance assessment outside VR (far transfer). These results suggest that real time-biofeedback in stressful and active action contexts can help train professionals such as police in real-life stress regulation.**

***Index Terms*— Biofeedback, Decision-making, Emotional control, Police training.**

I. INTRODUCTION

First responders such as police officers are routinely asked to make critical decisions under great pressure in the line of duty. Mistakes in such contexts can have grave consequences. Among the key factors contributing to inappropriate responses in such situations are psychophysiological arousal, subjective stress, and maladaptive emotional behavior [1], [2]. Indeed, acute stress decreases shooting performance in police[3], [4], and impairs decision-making [5]. In this work, we aimed to provide a motivating new tool for training physiological self-control in moments when it matters most.

The behavioral changes witnessed in stressed and threatened police officers are supported by the rapid reactions of the autonomic nervous system (ANS; [6]). Upregulation of sympathetic ANS activity serves rapid fight-or-flight reactions relevant for survival [7], [8], whereas concurrent upregulation of parasympathetic ANS arousal prevents the system from overshooting, facilitating bottom-up perceptual processing, action preparation and optimized decision making [9], [10], [11]. Stress-induced sympathetic arousal has been linked to reduced impulse control, attentional narrowing and eventually habitual, rather than flexible, instrumental responding [12], [13], [14]. Therefore, an adequate balance between sympathetic and parasympathetic autonomic arousal appears essential for more controlled performance under threat [15], [16], [17].

To enhance parasympathetic activity and mitigate the negative effects of stress, deep diaphragmatic breathing can be employed [18], [19]. This enhances parasympathetic activity as indexed at the level of the heart by respiratory sinus arrythmia: the acceleration of the Heart rate (HR) during inhalation, and HR deceleration during exhalation [20], [21], [22]. Normally, HRV is reduced under stressful conditions [23], [24]. A robust literature has indicated that breathing-induced increases in Heart-Rate Variability (HRV) may improve behavioral flexibility and control [25], [26], [27].

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Biofeedback (BF) has been employed as a targeted intervention to (1) raise awareness of currently experienced physiological stress, to subsequently (2) increase self-efficacy to instrumentally control one's own physiological reactions [28], [29], [30], [31]. This is achieved by presenting the user with feedback on their physiological state in a closed-loop reinforcement learning system [32]. One of the most frequently used and successful BF interventions to control stress-induced arousal involves operant conditioning procedures to deepen and slow breathing which, in turn, enhances heart-rate variability (HRV; [19], [33], [34]). Slow deep breathing synchronizes the HR with respiration, thus enhancing respiratory sinus arrythmia [22] which is indicative of vagally mediated relaxation [35] and linked to effective coping [34], [36]. Mounting evidence has shown HRV upregulation is effective in reducing anxiety [37], depression [38], cognitive performance [33], athletic performance [39], [40] and helps primary responders, such as police officers cope with stressful aspects of their job [30].

Despite its promise, widespread implementation of BF procedures is currently hindered by the fact that (1) current BF procedures are typically performed in a non-engaging way that requires high internal motivation and is not appealing for many users [41], [42], and (2) trainings take place in a non-arousing, passive setting while application is typically expected in action and under stress, thereby hampering transfer to real world use [43], [44]. Here we aimed to mitigate these problems by providing real-time BF in a newly designed engaging, stressful and active VR-gaming context.

Contextualizing BF training in a game that creates an engaging narrative may improve BF trainability [45], [46]. Demonstrated positive effects of such "gamification" include enhanced positive affect, immersion, improved participation and ultimately improved skill acquisition [47], [48], [49], [50], [51], [52], [53]. These improvements have been theorized to rely on several core principles, including provision of immediate feedback and individually relevant positive reinforcement [48]. Contextualized BF has moreover been shown to enhance transfer effects when compared to standard biofeedback techniques [51], [54].

Beyond engagement, we propose that stress regulation training can profit from training under safe yet arousing conditions. Stress is known to impair the retrieval of previously learnt information [55], [56], which can have severe consequences for when skills acquired under low-arousing conditions require transfer to stressful situations. For example, shooting performance in police has been shown to be severely compromised under pressure compared to low arousing conditions [4], [5], [57]. Importantly however, studies have shown that the negative effects of stress on retrieval can be mitigated by aligning training and application context [58]. For example, shooting performance in police officers under pressure can be substantially improved by practicing under pressure [4], [57]. This framework for improving transfer to stressful situations by training in high arousal situations has however not been applied in biofeedback applications to control stress. Such trainings are almost without exception performed in low arousing classroom or laboratory setups [30], [54].

Virtual Reality (VR) has been shown to be effective as a tool to create an engaging and arousing active context to train HRV upregulation when it is most needed and most difficult to attain [59], [60], [61], [62], [63]. Several applications have been recently designed to merge VR games with BF [53], [62], [64], yet these require very little arousing action, potentially due to the challenges of adapting BF biomarkers to motion artifacts [65] and the difficulty of designing serious games that can elicit genuine emotions and behaviors [66].

In light of these theoretical considerations, we recently developed and piloted a VR game for BF training in an active decision-making context in collaboration with the Dutch police [65], [67]. The VR game called DUST (Decision Under Stress Training; see Figure 1) draws inspiration from the popular genre of zombie shooter games which, even though they contain highly unrealistic narratives and stimuli, elicit high engagement and arousal [68] that could be related to experiences in real policing situations, thus potentially leading to increased transfer [69]. The choice to use a non-realistic game [49] was further motivated from the fact that realistic environments are expensive to develop and that small deviations from reality in realistic environments create a risk of feeling especially uncanny to the user [70]. In addition, realistic stress-inducing environments could potentially de-sensitize police officers to situations where civilian lives are at risk and over train strategies that in the complexity real-world can be maladaptive [71]. This is important as defining "good policing" is sometimes challenging in real settings and highly dependent on the context [72], [73] with complex social interactions that can be difficult to capture in VR. A game-like training environment can provide an engaging narrative for clear-cut go/nogo decision-making allowing for feedback that is both straightforward and comprehensive [74].

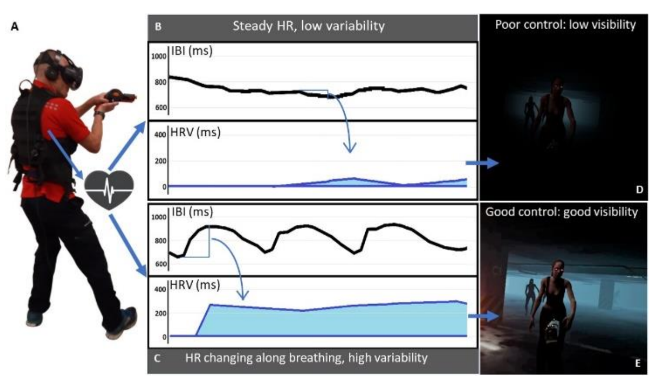

Fig. 1. Implementation of biofeedback (BF) as closed-loop peripheral vision modulation to reflect the negative consequences of attentional narrowing (tunnel vision) occurring under stress. (A) A police trainer in the VR game-context representing an underground parking lot, with zombies approaching. Critically, the game reacts to the real-time physiology of the participants, by restricting their field of view when HRV is low. (B) Example traces of inter-beat-intervals (IBI) and associated HRV when the participant's HR is stable and does not fluctuate along breathing, (C) IBIs and associated HRV traces when the participant's HR is in coherence with deep breathing (accelerating with inhalations and decelerating with exhalations); smaller fluctuations (less coherence) correspond to a lower HRV score and worse visibility (D) while large HR fluctuations (high HRV) were associated with good visibility (E).

In the present pre-registered study (*https://osf.io/cdsbx*), we comprehensively test an adapted version of DUST in a large police sample to assess whether DUST can train voluntary HRV control in arousing action contexts, and most importantly whether this skill transfers to a professionally relevant real-life action context. To the core game dynamics leading to engagement and arousal, we added mechanics representing psychological processes known to be impaired by stress-induced arousal: psycho-physiological self-regulation related to the parasympathetic nervous system [33], [36], Go/No Go decision-making for response inhibition [75], [76] and a priming task to assess bias resistance [77], [78]. Based on pilot work [67] we shortened VR sessions and implemented an improved biofeedback algorithm directly rewarding HRV instead of breathing pace to maximize training efficacy with a more cost-efficient set-up. This training targets local power HRV [79], which rewards respiratory fluctuations in HR, a widely used index of relaxation [22], [34], [35], in setup that provides a high-level resistance to movement artifacts [80].

The study had three objectives. First, we aimed to validate DUST as a believable and arousing virtual environment. We expected robust increases in arousal (HR) and in-game behavior consistent with this, such as the presence of false alarms [67]. Second, we aimed to test the efficacy of the game to train HRV self-control in an engaging manner. Therefore, we assessed the causal role of the BF by addition and withdrawal of the BF component in the game. As the subjective experience is considered a critical determinant of training motivation and success [28], [48], we evaluate how the game is perceived and assess perceived self-efficacy and physiological awareness. Finally, and most critically, to measure if the acquired voluntary HRV control transfers to the real world, we tested whether the HRV control would transfer to a police-relevant action context outside the VR game.

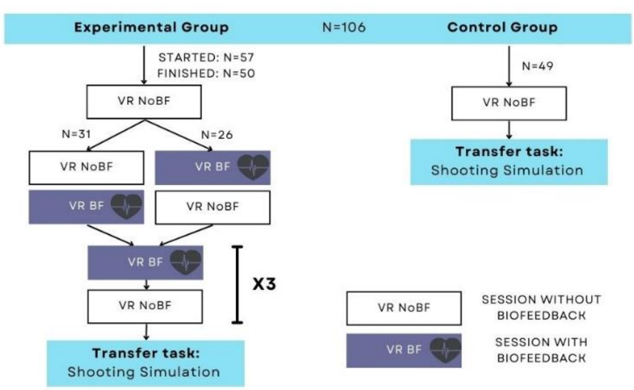

Fig. 2. Participant flowchart and design outline. The experimental group received 9 VR sessions, alternating sessions with online HRV BF and without, while the control group only received 1 session, without BF. In the experimental group, half of the participants received BF for the first time in the second VR session, whereas the other half received BF only in the third session. After the training, both groups performed a police-relevant transfer task to verify whether physiology and behavior were improved by the training.

II. Methods

Participants

In this pre-registered study (https://osf.io/cdsbx), participants were 109 police trainers aged between 30 and 60 years[1] (94 males, 15 females), with an average of 11.91 (*SD* = 10.652) years of operational policing experience. Most of the participants (*N*=64) indicated little (*N*=17) to no (*N*=47) familiarity with VR, while 29 others indicated a higher level of familiarity with VR. Participants were all trainers recruited via internal advertising from Dutch Police Training centers as well as from the police academy, which consists of several geographically dispersed locations throughout the country.

We designed our study as a quasi-random “pragmatic” control trial [81], [82]: Police trainers were assigned to an experimental or a control group, based on their availability. This method ensures enough randomization in the samples as the selection criterium is not related to motivational factors, nor handled by the researchers [82]. Indeed, the two groups did not differ in terms of VR experience ($t(108) = -.418$, $p = .677$), years of operational policing background ($t(108) = 2.036$, $p = .412$) nor HRV at baseline ($t(102) = -.570$, $p = .570$). Both groups took part in an independent task at the very end of the experiment, referred to as the “transfer task” (see Figure 2 and Materials section below).

Participation was voluntary and coordinated by the managers of the various training centers. According to the rules of the Dutch Police regarding research, financial compensation of the police trainers functioning as participants was not allowed. Therefore, a donation of 25 euros for each participant of the experimental group and 5 euros for each participant of the control group was allocated to a police charity fund. The research was approved by the ethical committee of the Faculty of Social Sciences of Radboud University Nijmegen. All participants provided informed consent in writing prior to participating in the study, in line with the guidelines of the Declaration of Helsinki [83].

Procedure

The full experimental procedure is illustrated in Figure 2. The experimental group took part in a nine-session training, spread over different days, spanning about one month. The number of sessions was determined based on results from an earlier study [67], which indicated a plateau in performance increases toward the 8th session and intended to strike a balance between efficacy and feasibility for implementation. Each session consisted of a VR session, alternating between a session without BF and one with BF. This alternation was used to both promote transfer (the player still received an overall biofeedback score at the end of each session) and to assess transfer effects. Furthermore, to be able to verify whether changes in physiology in the experimental group are related to the BF component of the game, in session 2 the BF component was introduced to half of the participants and only in session 3 to the other half of the participants (see Figure 2). To briefly practice HRV upregulation skills outside VR, both sub-groups

[1]In agreement with the Dutch police exact age was not recorded in this study to safeguard anonomity of the police trainers (about 25% of total number of IBT police trainers in the Netherlands participated in this study)

had a very short external BF training session in front of a laptop right before the first BF session. In line with recommendations for neurofeedback research [84], the control participants were passive controls and only played one VR session in the same game, but without any BF, during or after the session.

Materials

Physiological Recordings

Participants' HR were measured using a Polar H10 heart-rate sensor, where the HR corresponds to the time between consecutive R-waves of the QRS complex. This HR sensor reliably extracts R-R intervals, even under intense physical activity [80].

The Virtual-Reality Material and Game

The VR equipment used was an HTC Vive setup, with one of the two controllers wrapped by a 3D printed case used to give the controller the approximate shape of a gun, and the exact weight of the Walter P99 QNL gun that is used by the Dutch police. The other controller was used as a dispatch-radio controller and attached to the participant's vest. A thorough description of the game and design choices can be found a previous theoretical paper [49]. The VR game was adapted after a first feasibility study by Michela et al. [67]. The full list of adaptations can be found in the Supplementary Materials B. Briefly, the VR game mechanism was designed to resemble commercially available zombie shooter VR games. At the beginning of the game, the player was teleported to the center of a large parking lot and instructed to "protect" the location against zombies announced as aggressive by radio messages. The radio message was recorded to resemble real dispatch information both in terms of structure and tone. In each VR session, 5 to 6 zombie waves approached the player, each one preceded by a radio message announcing to the player which zombie type should be shot (hostile zombies that attack the player once in range) and which one should be spared (benign zombies that dissolve after reaching the player). The hostile/benign ratio varied between VR sessions but was kept around a 65/35% ratio as it maximizes the chances of false alarms [85] and therefore mitigates risks of ceiling effects in go/no-go performance. The radio dispatch contained two pieces of information to identify hostile zombies (e.g., "Shoot only the zombies with red eyes, we expect them to be large males"). The first part of the dispatch information was the eye color of the hostile zombies (red, yellow or blue). Eye color allowed to accurately identify hostile zombies but was hardly visible at a large distance. The second part of the dispatch information was the body type of the hostile zombies (male/female, small/large). This information was visible from a large distance, but was less reliable, thus priming the player to shoot benign zombies. Three different variations of the VR scenario were used in the game, distinguished by a task-irrelevant stressor comprised by a loud noise that was varied to increase unpredictability (glass shattering noise, car alarm, and fire alarm).

Biofeedback Parameter and Implementation

Breathing-induced fluctuations of inter-beat-interval were calculated by means of local-power HRV [79]. Only in BF sessions, higher local-power HRV was rewarded by unimpaired vision in the VR game whereas lower local-power HRV was progressively punished by reducing the player's field of vision (see Figure 1). Session order was AABBABABA or ABABABABA depending on the experimental subgroup (A = without BF; B = with BF; see Figure 2). In the sessions without BF, the vision of the player was not modulated based on HRV, and therefore always unimpaired. This addition and withdrawal methodology, inspired by small-N designs [86], [87], was taken from our first qualitative study [67] and conserved in this larger study. The local-power HRV was calculated with the Python-coded "OpenHRV" program [88], which extracts peak-trough differences in a 15 second sliding window of the inter-beat RR intervals. The BF score, varying between 0 and 1, was then calculated based on the Local-Power HRV. The initial target for the HRV was set to peak-troughs differences of 100ms, but could be adapted for each participant in the game to maximize learning. With the standard target, a local-power HRV of 100ms and above would lead to a BF score of 1 (maximal visibility for the participant in the VR experience). The score would then linearly decrease to 0 for local-power HRV = 0ms, leading to a severe visual impairment for the player, with restricted peripheral vision to the point where only zombies directly facing the player would be visible.

Questionnaires

Engagement questionnaire. Engagement was measured once at the end of the full training with a four-item questionnaire [89] on a 7 points Likert scale (1=Strongly disagree, 4=Neutral, 7=Strongly agree). The final score was obtained by averaging the answers on all items.

Physiological awareness questionnaire. Physiological awareness was measured after every VR session, through a two-item questionnaire asking how aware participants were of their breathing and of their HR during the VR task. Each question could be answered with a 7 points Likert scale (1=Strongly disagree, 4=Neutral, 7=Strongly agree).

Exit questionnaire. At the end of the full training, the experimental group received an exit questionnaire aimed at evaluating the degree of satisfaction of the training (e.g., "Would you use this VR environment in your teaching?") and the subjective experience in the game (e.g., "How stressed were you in the VR environment?"). The full list of questions can be found the Supplementary Materials A.

Transfer Task

To assess if the training in the VR game would carry over to relevant policing behavior outside the game, a police-relevant task was designed drawing inspiration from the dispatch-priming paradigm of Taylor [80]. The task consists of a single shoot-don't shoot decision toward a target taking an object out of their pocket (a gun or a phone), projected on a screen. The decision moment was preceded by a radio dispatch message describing the appearing target as either an armed and violent opponent (priming the participant to shoot), or as an innocent passer-by. In our version of the task, the radio message always primed the participant for a violent perpetrator, and the target always drew a phone out of their pocket in the first (critical) trial. Participants were asked to keep their finger on the trigger and refrain from moving. Three distractor trials were added after the first critical No-go trial to obscure the purpose of the experiment. In those trials the subject appearing on screen took a gun instead of a phone out of his pocket and held it for 3 seconds before the next trial. In these trials the correct response was to shoot the opponent. Data from these trials were not analyzed.

Data Preparation

Physiological recording

The HR of the participants was analyzed separately for baselines (preceding the odd numbered VR sessions), in-game VR sessions (with and without BF) and during the transfer task following the last session. HR in beats per minute were used both in absolute values as well as relative changes from baseline (baseline-corrected HR), in which case the baseline value was subtracted from the in-game value. Prior to feature extraction, the data was cleaned automatically to remove artifacts with the Python software Biopeaks [90], which used the artifact correction for HRV timeseries proposed by Lipponen & Tarvainen [91]. Mean and median HR were extracted for each condition. Finally, the mean and median Local Power HRV [79] were calculated per condition (with or without BF). For each of those sessions, frequency-based HRV metrics were not extracted if the recording was shorter than 5 minutes, and Local Power HRV was not extracted for recordings shorter than one minute [79].

Decision-making and monitoring

The number of hostile zombies shot before reaching the player represented hits, while hostiles who reached the player before being shot were the false negatives. Non-hostile zombies reaching the player were correct rejections, and if shot by the player they were false alarms. Those four sums were then used to calculate in each VR session the sensitivity {d’ = [z(Hit rate)−z(False alarm rate)]} according to signal detection theory [92]. Further, the number of “unspotted targets” (both hostile and benign), that is zombies reaching the player without ever appearing in their field of vision, were counted as a measure of spatial awareness.

Data Analysis

The following section describes the pre-registered hypotheses (https://osf.io/cdsbx) as well as additional exploratory analyses. The main reason that our analyses deviate from the pre-registered analyses is because the dataset was not complete due to attrition and poor data quality for some participants (see Supplementary Materials C, Table S10, for a complete list of analysis modifications). Hence, repeated-measures ANOVAs with list-wise deletion resulted in too much data loss. Therefore, all repeated measures analyses were replaced by Bayesian mixed-effects models, computed in R (Version 3.5.1; R Core team, 2016) using RStudio (Version 1.4.1717; RStudio Inc., 2009–2021) with the brms toolbox (Version 2.17.0; [93], [94]). In these models the effect of time was investigated by contrasting the first and the last of the VR sessions. All categorical predictors were coded using sum-to-zero contrasts, and continuous predictors were zero-centered. As the data contains repeated measures, the models included random intercepts and slopes per participant for all relevant predictors. Interactions and full models’ descriptions can be found in Supplementary Materials D. We fitted the models using 4 chains with 15000 iterations each (6000 warm-up). Statistical “significance” was derived from 95% posterior credible intervals that did not include zero. To provide more information on the robustness of a significant result, each analysis was performed with credible intervals at 90%, 95%, 99% and 99.9%. We always report the significant result with the more conservative credible interval (similar to reporting *p*-values smaller than a certain value).

VR Game Validation

As one of the central design tenets and innovations of the game was to train HRV under high arousal, we compared baseline HR to average HR in the subsequent VR session, across all participants (experimental group and controls). Importantly, HR was only used to have a proxy measurement for arousal and was never directly trained, since only the variability in HR was the target of BF due to its more direct association with parasympathetic control [33], [36]. A paired t-test comparing the first session of gameplay to the baseline immediately preceding it was complemented with mixed effects models with condition (with or without BF) and session number to assess increase relative to baseline also for later sessions.

For behavioural verification we assessed whether participants showed priming of their shooting behaviour. The radio message preceding each zombie wave contained two pieces of information to describe target zombies (e.g., “Target zombies will have red eyes (1), and we expect them to be large males (2)”). Eye color directly identified targets but was more difficult to identify especially from a distance, while morphology was easily recognizable but not always accurate. This was expected to lead to an increase in false positive responses against zombies that had the primed body type, but a different eye color (and were therefore actually not hostile targets).A pairwise t-test evaluated if participants from the control and experimental group in the first session shot significantly more non-hostile zombies (FA) when the morphology of these zombies was announced by the radio dispatch information as potentially hostile (dispatch-primed FA), compared to FA happening when the body type of the zombie did not match dispatch information. As for the HR analysis, this analysis was complemented with a mixed-effect model including priming (primed vs unprimed) and session to assess whether differences between primed and unprimed FA existed in the subsequent VR sessions played by the experimental group.

Effectiveness and appraisal of the training

To investigate the effect of biofeedback on the HRV of participants, a first mixed effect model was run to evaluate the effect of condition (with and without BF) on HRV in the sessions after the first playthrough. The model beyond condition also included predictors session and subgroup (A/B see next analysis). To assess increases over sessions for each condition, we compared the first and the last session. The causal influence of the BF was investigated further by assessing the effect of introducing BF in different sessions for the two subgroups (A and B) of the experimental group. Three *t*-tests were preregistered to test if there was a difference in HRV between these subgroups in the first VR session where no participant had yet received BF, in the second VR session where only group B had BF and in the third session where only group A had BF. The HRV averages and standard error of each session are reported in Figure 3.

To investigate if the breathing and HR awareness and self-efficacy of the participants changed throughout the training, we ran a mixed-effect model for each measure with session and condition as random slopes and intercepts. In addition, we directly tested for increases from the first to the last session. An additional mixed effect model was run with data from session 2 to session 9 to investigate the effect of condition and time on self-efficacy. The breathing and heart awareness averages are reported in the first panel of Figure 4, while the second panel represents the averages of self-efficacy. In both panels, subgroup "a" was merged to subgroup "b" to represent the general trend. Further, the engagement of the experimental group throughout the training was evaluated by testing the score of the engagement questionnaire against the value 4 in a single sample *t*-test. A value of 4 represents appraising the VR game as neutral. The same test was run for the scores of training usefulness and efficacy. The third panel of Figure 4 represents the average rating for the usefulness, efficacy and engagement scores.

Lastly, the relation between the *in-game* HRV of the participants and their behavioral performance was evaluated with a mixed-effect model. The model was evaluating if the d' sensitivity could be predicted by HRV, with time and condition as additional predictors. The same analysis was also reproduced for FA and unspotted targets.

Skill transfer

A chi-squared test was performed to evaluate if the experimental group made less mistakes than the control group in the first trial of the transfer task. The two levels were shooting behavior (shot/withheld shot) and group (experimental vs. control). Independent sample *t*-tests were done to test if there were differences in HR(V) during the transfer task between groups.

III. Results

A list summarizing all the results can be found in the Supplementary Materials C, Table S10.

Objective 1: VR game validation

First, we evaluated whether the game produced the intended increase in arousal, evaluated as an *in-game* increase in HR from baseline. Across both the experimental and the control groups, in the first session of playing the game, *in-game* HR (M = 93.39, SD = 17.84) increased robustly when compared to baseline before gameplay (M = 80.04, SD = 13.97; $t(83)$ = -14.554, $p < 0.001$; see figure 3A). Also, across all successive sessions for the experimental group, mean in-game HR was highly significantly increased compared to baseline both in sessions with and without BF (N = 57, B_{bf} = 10.57, 99.9% CI [7.43, 13.70]; B_{nobf} = 9.91, 99.9% CI [6.97, 12.82]; though slightly reduced over time; further details see Supplementary Materials A). Despite the robust increase in psychophysiological arousal, police trainers rated the experience as mildly stressful (M = 3.54 on a 7-point scale), not unexpected given previous underreporting of experienced stress in police [95].

Given the arousal induced by our game, we expected difficulties in the inhibition of automatic response tendencies. While there was no difference in the first session between false alarm rates for primed and unprimed non-targets ($t(110)$ = -0.52, p = 0.604; M_{primed} = 1.65, SD_{primed} = 1.82, $M_{unprimed}$ = 1.75, $SD_{unprimed}$ = 1.617), later sessions (2 to 9) showed that false alarms were on average higher for the primed non-targets ($B_{priming}$ = -0.56, 99.9% CI [-0.91, -0.23]; M_{primed} = 1.43, SD_{primed} = 0.96, $M_{unprimed}$ = 0.86, $SD_{unprimed}$ = 0.61). Thus, our game produced the expected increases in arousal and required participants to inhibit primed pre-potent responses.

Objective 2: Effectiveness and appraisal of the training

Every participant of the experimental group started with a session of gameplay without biofeedback to get accustomed to the gameplay. Afterwards, presentation of the BF consistently resulted in higher HRV (regardless of whether it was introduced in session 2 or 3; N = 57, across sessions $B_{BF\_vs\_nobf}$ = -5.42, 99.9% CI [-10.03, -0.43]). From the moment BF was introduced HRV remained high from the first to the last BF session (reflected in an absence of significant increases from the first to the last session). Interestingly, the ability to upregulate HRV in action in the absence of BF developed gradually (see Figure 3A), with a robust increase between the first and the last non-BF training session ($B_{S9\_vs\_S1}$ = 11.39, 99.9% CI [2.10, 21.08]). Overall, the in-game HRV of the experimental group went from 39.77ms in the first session to 52.67ms in the last session, a 32% increase.

To assess the causal influence of BF on the HRV, and to rule out that the observed increases in HRV were chiefly caused by repeated exposure to the game rather than BF presentation, we subsequently compared sub-groups for whom BF was introduced at different sessions (group a: session 3 vs. group b: session 2; see Figure 3B). Confirming our preregistered hypothesis that the BF drives HRV upregulation, we found that in session 2 the introduction of the BF in group B significantly increased HRV compared to group A that played this session without BF (M_a = 38.27, SD_a = 19.30, M_b = 60.08, SD_b = 26.77; $t(49)$ = -3.347, p = 0.002). We subsequently verified that the significant group difference was not present in session 1 where both groups played without BF ($t(42)$ = -1.574, p = 0.123), nor in session 3, after BF was introduced also in group A ($t(50)$ = -1.016, p = 0.314). Thus, our results suggest that changes in HRV were causally induced by BF.

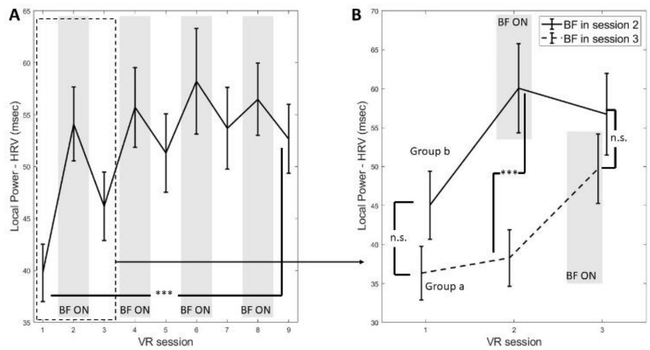

Fig. 3 Evolution of the Mean Heart-Rate Variability (HRV) in the Experimental Group. (A) across time and condition for the entire experimental group; (B) for the 3 first VR sessions, where BF was introduced in the second session for half of the experimental group (labelled as group b, N = 26) and in the third session for the other half (group a, N = 31). The results show that BF consistently led to increased HRV over the BF sessions, which gradually transferred to the non-BF sessions (A), and that the HRV increase after the first session is causally related to the moment of BF introduction (B); For all figures: BF ON = session with online BF presentation; error bars represent standard error of the mean; *** = 99,9% CI not overlapping with zero.

After having established the expected BF training-induced HRV-increase, we tested how the training impacted the evolution of physiological awareness. Subjective awareness of breathing increased robustly from the first to the last session (N = 57, B $_{S\_9vsS\_1}$ = 1.99, 99.9% CI [1.05, 2.98]). Also, awareness of heart rate increased substantially throughout the training (N = 57, B $_{S\_9vsS\_1}$ = 1.19, 99.9% CI [0.21, 2.16]). Although no significant increase over sessions was found for self-efficacy, which was contrary to our expectations, it was lower in BF sessions ($B_{BF\_vs\_NoBF}$ = -0.36, 99.9% CI [-0.69, -0.05]) indicating that the BF signal may have reminded police trainers that the in-game HRV self-control was challenging. However, the training was perceived positively by the police trainers as evidenced by high post-training ratings of engagement, usefulness and efficacy (on 7-point scales, useful M = 5.72, efficacious M = 5.41 and engaging M = 4.9), all significantly positive (tested against preregistered reference value of 4 = neutral anchor in the Likert scale; $t_{engage}(52) = 10.76$, $p < 0.001$; $t_{use}(52) = 13.42$, $p < 0.001$; $t_{eff}(52) = 8.49$, $p < 0.001$). Illustratively, 80.76% of the police trainers responded positively to the question whether they would like to use this game in their own training program.

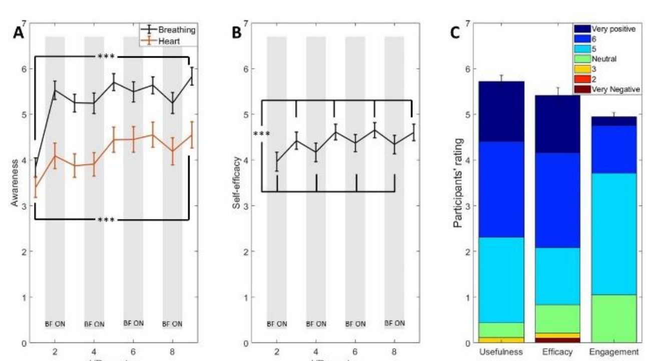

Fig. 4. Police trainers' appraisals and perception of the training. Evolution of the (A) interoceptive awareness (breathing and HR) and (B) the self-efficacy, across time and condition for the entire experimental group; (C) Rating of the experimental group for the perceived usefulness and efficacy of the training, as well as the elicited engagement; Colors indicate the distribution of participants' responses and indicate the perception was overwhelmingly positive.

Next, we tested whether the effort of focusing on HRV increases did not lead instructors to neglect behavioral performance. As illustrated in Figure 5, the sustained improvements in HRV observed in Figure 3 went together with improvements in behavioral performance when comparing the first and the last VR session, both in FA reduction ($B_{S9\_vs\_S1}$ = -1.49, 99% CI [-2.83, -0.20]) and spatial awareness (unspotted targets; $B_{S9\_vs\_S1}$ = -1.09, 99% CI [-1.95, -0.20]). General shooting behavior, measured as the d' sensitivity index from signal detection theory [92] did not change significantly from first session, but exhibited a positive trend ($B_{S9\_vs\_S1}$ = 0.16, 90% CI [0.01, 0.30]). While the improvements in behavior suggest that participants' performance may have benefitted from improved HRV self-control, there was no correlation between session-by-session behavioral and physiological changes (d'; B_{HRV} = 0.04, 95% CI [-0.07, 0.15]; FA; B_{HRV}= -0.09, 95% CI [-0.68, 0.52]; unspotted targets; B_{HRV}= 0.08, 95% CI [-0.33, 0.48]).

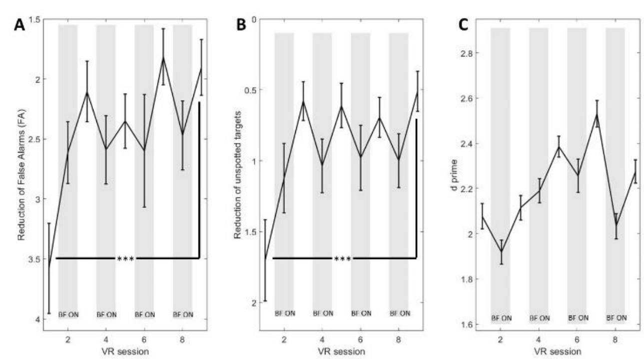

Figure 5: Evolution of the main behavioral metrics across time and condition for the experimental group; (A) False Alarms (FA); (B) Unspotted targets: number of targets that were able to reach the player without being detected; (C) Evolution of the player's target sensitivity (*d'*); NB. the phasic drop in *d'* in the 8th session is due to an unexpected increased number of false negatives.

Objective 3: Skill transfer

Finally, and most critically we tested whether the ability to voluntarily upregulate HRV demonstrated in the game transferred to an independent, realistic professionally relevant assessment outside VR (see Figure 6 panel A). As only the first trial could be used for behavioral assessment (subsequent trials were distractors), this task was not optimized for evaluating the effect of the training on shooting tendencies and no difference in behavioral performance between the control and experimental groups was apparent (X^2 (1, N = 100) = 0.09, p = 0.764; percentage Go responders per group 40.4% control group; 43.4% experimental group; for details see Supplementary Materials A). Also, during the transfer task, physiological arousal of both groups (HR) did not significantly differ ($t(81) = -0.240$, p = 0.811; M_{exp} = 87.04 bpm, SD = 13.94, M_{contr} = 88.16 bmp, SD = 14.88) while staying significantly higher than baseline, thus indicating elevated arousal at test ($t(74) = -8.360$, $p < 0.001$; $M_{transfer}$ = 87.04 bpm, SD = 13.94, M_{base} = 80.424 bmp, SD = 13.48). Critically, the experimental group did show significantly higher HRV already during the baseline before the transfer task ($t(94) = 2.106$, $p = 0.038$, M_{exp} = 68.63 ms, SD = 36.82, M_{contr} = 55.36 ms, SD = 23.78) and more importantly HRV was also robustly higher during the transfer task ($t(81) = 2.986$, $p = 0.004$; M_{exp} = 58.77 ms, SD = 24.25, M_{contr} = 44.35 ms, SD = 20.33; see Figure 6 panel B). To ascertain that this effect was not due to pre-existing group differences, we compared HRV between groups during the baseline of the first session (i.e. before the experimental group was trained). As expected, there was no significant difference between the groups at this time (day 1; t(102) = -0.570, $p = 0.57$, M_{exp} = 57.94 ms, SD = 22.26, M_{contr} = 55.36 ms, SD = 23.78). The critical group difference during the transfer task also remained significant when controlling for pre-training HRV levels (session 1 baseline; $t(72.88) = -3.224$, $p = 0.002$; corrected for variance inequality). Together, our results support the conclusion that the experimental group showed increased HRV at transfer following our VR training.

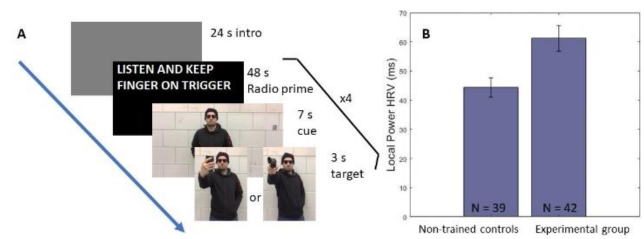

Fig. 6. HRV local power in the independent professionally relevant (non-VR) transfer task. (A) transfer task design; Intro: participants were instructed that they were in a shoot/don't shoot decision task and asked to listen to radio dispatch; Radio prime: A realistic police radio dispatch primed the participant by describing a violent perpetrator asked to keep weapon pointed at screen; Cue: a target that matches the description appears; Target: target draws a gun/phone from their pocket; Response: participant is required to withhold (No-go) when a phone appears, or shoot when a gun appears; (B) Absolute Local Power HRV (difference in ms) between the non-trained control and the experimental groups for the critical preregistered comparison during the transfer task; Error bars represent standard error of the mean.

IV. Discussion

This preregistered quasi-randomized controlled trial among 106 police trainers provides the first evidence that HRV-BF training in an arousing VR action game can be used to (1) boost voluntary HRV upregulation in professionals with improved concurrent decision making under threat and (2) enable skill-transfer to both an in-game session without BF and an independent professionally relevant real-world testing context. By systematically varying the moment of BF introduction, we further provided evidence that the increases in HRV were causally linked to our in-game BF presentation. Furthermore, the game produced substantial increases in self-reported physiological awareness and was rated a useful, efficacious and engaging training tool by a large majority of the police trainers assessed.

Our contextualization of the biofeedback with an arousing action game format contrasts with other (VR) biofeedback approaches that have typically trained stress resilience in calming virtual environments [41], [42], [64]. DUST induced substantial HR increases during gameplay, in the same order of magnitude as found in established stress-induction protocols [96], [97] and fear induction in VR [68]. The use of real-time in-game biofeedback allowed players to recognize stress-induced reductions in HRV and at the same time motivated them to upregulate their HRV. The difficulty of the resulting 'dual-tasking' in BF conditions (i.e. playing and regulating concomitantly) was reflected in the police trainers' consistent reports of a reduced feeling of self-efficacy in BF versus non-BF sessions. However, physiological awareness steadily increased with training and this reflects that the police officers were in fact learning *in-action* psychophysiological regulation. Interestingly, the increases in HRV induced by the present BF training are comparable in magnitude to the BF training-induced changes in seated and non-active setups [98]. This is noteworthy as our participants were experienced police trainers, previously trained with more traditional passive biofeedback and therefore may have been expected to show already strong HRV regulation skills from the start. In sum, we showed that contextualizing biofeedback by adding arousal, movement, and active decision-making does not prevent the learning of voluntary HRV upregulation in action and provides benefits even in participants experienced with HRV biofeedback.

Besides the goal of making the training enjoyable and challenging, the most important aim of the arousing action context was to promote transfer to arousing situations outside of the game. Our results showed transfer of HRV upregulation not only to a context without BF within-game (near transfer), but also to an independent non-VR task (far transfer). So far, no HRV-BF studies have reported transfer of HRV upregulation skill outside of the training environment [42]. These results extend previous literature indicating that HRV biofeedback in passive and calm settings can enhance HRV control [31], [34], [99]. While studies with such non-immersive biofeedback can already lead to significant benefits beyond the training setting such as increased physiological control and improved decision-making under stress [29], [100], immersive VR based biofeedback can offer advantages beyond this, by enhancing motivation [42], [64] and gamification which has been shown to aid transfer to real-world settings [51], [54], [101], [102]. Importantly, the reported difference in HRV between the experimental and the control group cannot be attributed to a larger familiarity of the experimental group to the research setup, since the transfer task was new to both groups. A notion that was further supported by the absence of group differences in arousal (absolute HR) during the independent transfer task, despite the transferred HRV differences.

Previous studies have shown that higher levels of HRV are linked to a wide range of health and performance benefits [31], [34], [99]. While we observed improvement in in-game performance we could not observe any behavioral impact of the training on the transfer task, possibly resulting from the fact that our transfer task was not optimized for assessing behavioral differences and that these analyses were based on a single trial. Indeed, HRV trainings for police and military personnel that proved to be sensitive for measuring behavioral benefits were more complex simulations, also involving verbal communication [60], [100].

Game-based approaches have been shown to enhance motivation [46], a factor that has been identified as critical to foster change [103]. In line with this notion, our VR game was still rated as engaging after nine training sessions. Indeed, standard HRV trainings in passive sitting contexts are not always considered enjoyable, particularly in police officers [44]. We speculate, that the relative playfulness of our training game prevented this negative reception that has been linked to difficulties federating police trainers around a common learning goal [104], [105]. This notion is further supported by the finding that 80% of the trainers indicated they would adopt our VR BF game training in their own teaching.

Traditional randomized controlled trial designs can be used to assess the causal influence of an intervention, but usually cannot give a mechanistic account of what, in the intervention, drives the effect [106]. Our training schedule circumvents that limitation by drawing inspiration from designs commonly used in case reports. First, we used the delayed introduction of BF for part of the experimental group, as used in the multiple baselines design [107]. This design allowed us to further assess the causal role of BF presentation on HRV increases, as increases only happened after the introduction of BF. Second, we adopted an addition and withdrawal design [86], [108] by alternating BF and non-BF sessions, which allowed us to further strengthen the causal claim centered around BF presentation as its presence was linked to higher levels of HRV control.

Some limitations should further be discussed when evaluating these findings. First, the size of our sample was not sufficient to address sex and gender related differences in behavior, reception and outcome. Additionally, for privacy reasons we recorded no demographic information that could help to identify participants. Therefore, we could not verify if groups differed in age or gender distribution. Nevertheless, all trainers were within the age range of 30-60 years old and there were no statistical differences in years of experience between groups. Note that the latter measure is expected to be robustly correlated with age, adding to the assumption that there were no systematic age differences between groups. Regarding the evaluation of training effects, while our study provides important new evidence of HRV transfer of training to a new context, it would be important to establish also long-term effects on real-life policing outside a training context, or even on duty using wearables to assess psychophysiological arousal. Moreover, our transfer task was not suitable to assess training effects on behavior, which are typically found in decision-making tasks using actors, and thus featuring more complex and verbal dimensions of the policing and military work [60], [100]. Those complex behavioral dimensions (such as verbally interacting with a suspect, potentially leading to a shoot/don't shoot decision [100], or deciding to apply a medical procedure in a theatre of war [60] could also potentially be implemented in the VR training itself, by using now available artificial intelligence methods [109].

Additionally, although the training had a significant impact at group level, a minority of participants showed minimal improvements from the training and the current study did not assess potential individual predictors of training efficacy. These could be, psychological dimensions such as growth mindset [28]. Particularly interesting in this respect are also computational approaches that formalize distinct aspects of biofeedback learning and could therefore provide a better understanding of the mechanistic background of individual variation in biofeedback's efficacy [32].

While we have tested here the efficacy of our game in a group of police trainers, our approach of training HRV control under arousal could potentially also be relevant in different populations that suffer from negative consequences of stress. Indeed, unregulated high arousal during stressful events has been repeatedly linked to long-term trauma symptom development [110], [111], [112], [113]. As passive forms of HRV training have already been shown to alleviate symptoms in people suffering from anxiety and depression [37], [38], HRV training under arousing conditions may be especially useful for preventive efforts and our gamified biofeedback could provide motivational benefits also in other groups.

To conclude, this study presents a novel training method using a BF game in VR to help police officers cope with stressful environments while in action. The training was effective in fostering HRV upregulation even during high arousal and in action. Importantly, the training was also highly appreciated by the police trainers who underwent the training as participants. As police trainers are a population usually known to be critical towards innovation [114], [115], this provides promise for the adoption of this technological intervention also for other populations.

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