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# Testing the hormesis hypothesis on motor behavior under stress

Laura Voigt [a,b], Yannick Hill [c,d,e,*], Marie Ottilie Frenkel [a,f]

[a] Institute of Sports and Sports Sciences, Heidelberg University, Germany
[b] Institute of Psychology, German Sport University, Cologne, Germany
[c] Department of Human Movement Sciences, Faculty of Behavioral and Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam Movement Sciences, the Netherlands
[d] Institute of Brain and Behaviour Amsterdam, Amsterdam, the Netherlands
[e] Lyda Hill Institute for Human Resilience, Colorado Springs, USA
[f] Faculty of Health, Safety, Society, Furtwangen University, Germany

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ABSTRACT

While much research has focused on the deleterious effects of stress on goal-directed behavior in recent decades, current views increasingly discuss growth under stress, often assuming dose-dependent effects of stress in a curvilinear association. This is based on the concept of hormesis, which postulates a strengthening effect of stress at low-to-moderate doses. Leveraging this approach, hormetic curves indicate under which stress dose an individual is able to maintain or even increase goal-directed behavior. The present study aimed to test the hormetic effect of low-to-moderate stress on tactical movement performance in the context of police operational scenarios in virtual reality. In teams of three to four, 37 riot police officers had to search a building for a potentially aggressive perpetrator in three scenarios with escalating stress potential (i.e., increasing weapon violence and number of civilians). Tactical movement performance as behavioral response was quantified by the sample entropy of each officer's velocity derived from positional data. To account for inter-individuality in response to the scenarios, we assessed self-reported stress, anxiety, mental effort, and vagally mediated heart rate variability. Specifically, we tested the quadratic associations between tactical movement performance and stress parameters, respectively. Random-intercept-random-slope regressions revealed neither significant linear nor quadratic associations between any of the stress parameters and performance. While we did not find evidence for hormesis in the present study, it stimulates theoretical discussions about the definition of "baseline" functioning and how the understanding of hormesis can move from psychological to behavioral adaptations to stressors.

## 1. Introduction

In high-performance settings, individuals often need to maintain goal-directed behavior while interacting with stressors. For instance, a police officer needs to arrest a perpetrator while being threatened with a knife. Typically, research in such high-performance settings focuses on the deleterious effects of stress on goal-directed behavior, disrupting cognitive and motor processes (e.g., Beilock and Carr, 2001; Eysenck et al., 2007; Masters, 1992; Nieuwenhuys and Oudejans, 2017; Sullivan et al., 2022). However, emerging research discusses the beneficial effects of exposure to low-to-moderate stress levels on human behavior (e.g., Kiefer et al., 2018; Kiefer and Martin, 2022). The theoretical basis for the salutary effects of low-to-moderate stress is mainly drawn from experimental work in toxicology and is referred to as *hormesis* (Calabrese, 2005). Hormesis describes a pattern in which limited toxicological stress induces a strengthening effect, which, however, becomes detrimental beyond a specific threshold. This general principle has been translated – via the Yerkes-Dodson law (Yerkes and Dodson, 1908) – into a number of discipline-specific theories on the arousal-performance relationship in performance psychology (e.g., Hardy and Parfitt, 1991; Kerr, 1985). Moving beyond correlation studies, the present experiment aimed to test the hormetic effect of escalating stress doses on goal-directed behavior in a virtual police setting.

* Corresponding author. Faculty of Behavioral and Movement Sciences, Department of Human Movement Sciences, Vrije Universiteit Amsterdam, De Boelelaan 1105, 1081 HV, Amsterdam, the Netherlands.
*E-mail address:* y.hill@vu.nl (Y. Hill).

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### 1.1. Goal-directed behavior under stress

A large body of literature points to the assumption that psychological stress may harm cognitive and motor processes linked to goal-directed behavior in high-performance settings (e.g., Beilock and Carr, 2001; Eysenck et al., 2007; Masters, 1992; Nieuwenhuys and Oudejans, 2017; Sullivan et al., 2022). Psychological stress is understood as a state of threatened homeostasis which can be triggered by emotional and/or cognitive stressors, such as fear- and anxiety-producing threats, the anticipation of aversive states and experiences, scarcity of information, as well as time and work pressure (Bali and Jaggi, 2015). Psychological stress responses include emotional responses (e.g., anxiety), motivational states, and efforts to manage the affective and physiological arousal by means of emotion regulation strategies and coping efforts. Additionally, physiologically mediated processes that involve both the autonomic nervous system and the hypothalamic-pituitary-adrenal axis mobilize biological resources (e.g., energy such as glucose) to cope with the stress (Hermans et al., 2014; McEwen, 2007). These stress responses are usually considered adaptive, as they enable rapid threat detection and quick unpremeditated action. However, the majority of research focuses on the detrimental effects of stress on performance in the context of goal-directed behavior (for an overview see Nieuwenhuys and Oudejans, 2017), assuming disrupting effects on cognitive and motor processes (Beilock and Carr, 2001; Eysenck et al., 2007; Masters, 1992). Indeed, systematic reviews showed that acute stress degrades perceptual-motor performance (e.g., Nieuwenhuys and Oudejans, 2017; Payne et al., 2019; but see Sullivan et al., 2022).

Methodological limitations and the potential lack of group-to-individual generalizability of empirical findings (i.e., non-ergodicity) might have led to biased understanding, underestimating the human potential to perform under stress. The majority of studies have examined the effect of stress on goal-directed behavior in high-performance settings in binary study designs, comparing no or low levels of stress to relatively high levels of stress (e.g., Giessing et al., 2019; Lautenbach, 2017; LeBlanc et al., 2012; Nibbeling et al., 2014; Nieuwenhuys and Oudejans, 2010; Nieuwenhuys et al., 2008, 2012a,b; Renden et al., 2014, 2017). Such group-mean comparisons assume that performance under stress can be considered as ergodic, i.e., the underlying changes follow a common pattern across individuals and can therefore be generalized to the individuals in the sample (Molenaar and Campbell, 2009). However, psychological processes are typically individually variable and time varying. Thus, group-level trajectories may not represent the actual tendencies displayed by the individuals within a given sample, which is known as the lack of group-to-individual generalizability or non-ergodicity issue (Hamaker, 2012; Fisher et al., 2018; Molenaar and Campbell, 2009). Indeed, differential analyses have shown that not all participants exhibit performance decrements under stress. Some maintain or even increase their performance under stress (e.g., Geukes et al., 2012), a phenomenon that has been termed clutch performance (Schweickle et al., 2021). Of note, these differential findings may easily account for the inconsistent results on the effect of stress on performance in a recent systematic review (Sullivan et al., 2022).

The non-ergodicity issue might also be attributable to dose-dependent effects of stress on performance, when assuming non-linear dose-response dynamics (Kiefer et al., 2018). Specifically, participants may differ in their stress levels experienced in the respective experimental conditions and therefore, might perform differently in the same condition. In linear models of dose-response dynamics, subtle variations in elicited stress levels can be disregarded as noise, as any increase in stress should be associated with performance decrements. In contrast, in curvi-linear models, variations in elicited stress levels will result in different effects on performance. Specifically, individuals experiencing a low level of stress are likely to benefit from stress increase, whereas individuals experiencing a medium level in the low-stress condition are likely to show performance impairments with increasing stress levels (see Fig. 1). To account for the differential and inconsistent results in studies investigating performance under stress, nomothetic research assuming non-linear dose-response dynamics can help to examine inter-individual variability in stress reactivity and performance when facing different stressors.

### 1.2. Hormesis

Originated in the field of biology, toxicology, and medicine, hormesis refers to such dose-dependent effects of toxic substances, and postulates that the nature of the dose response observed in toxicology is not linear or threshold-based, but rather J- or U-shaped (Agathokleous et al., 2018; Calabrese and Baldwin, 2003; Costantini et al., 2010; Southam and Ehrlich, 1943; Stebbing, 1982). A hormetic dose-response pattern depicts the change in an organism's functional response relative to a baseline level (or lowest observed dose). Under low to medium doses, the response of the organism improves with increasing doses, until the pattern begins to reverse and increasing doses induce a decline in the organism's response. The resulting biphasic U-pattern can thus be divided into a region of apparent improvement (i.e., growth above the baseline) and a region of toxic or adverse effects (i.e., decline below the baseline, see Fig. 1). In performance psychology, the idea of non-linear dose-response dynamics is reflected in a number of arousal-performance relationship theories. These suggest positive effects of moderate stress levels on motor performance, but diminished performance with either

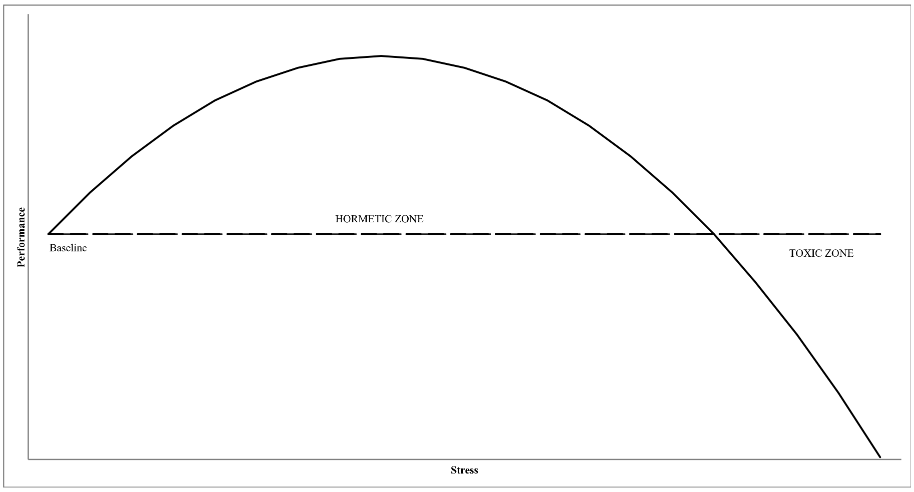


**Fig. 1.** Hormetic process.

too little or excessive stress (e.g., Hardy and Parfitt, 1991; Kerr, 1985). The models are based on the Yerkes-Dodson law (Yerkes and Dodson, 1908), which has been considered to constitute a discipline-specific case of the general concept of hormesis (Calabrese, 2005).

Despite these theoretical considerations, non-linear dose response dynamics of stress on human behavior have rarely been tested empirically. An inverted U-shaped effect of stress has been suggested for various cognitive functions, such as memory (Lupien et al., 2005), learning (Luksys and Sandi, 2011; Zoladz and Diamond, 2009), and decision making (Yu, 2016; also see Sapolsky, 2015). While correlation studies can easily depict the nonlinear relationship (e.g., Domes et al., 2004), these theoretical assumptions are often not reflected in experimental study designs which only incorporate two conditions (e.g., Haleem et al., 2015; Shields et al., 2019). Only rare exceptions employ a dose-escalating design with more than two different doses, to test a quadratic relationship between stress and cognition (e.g., Hepler and Andre, 2021; Schilling et al., 2013). Moreover, even these studies still do not incorporate naturalistic actions that are representative of goal-directed motor behavior in high-performance settings (Ibanez, 2022; Maselli et al., 2023).

### 1.3. Hormesis in goal-directed motor behavior

In line with calls for action-oriented paradigms (Ibanez, 2022; Maselli et al., 2023), we aimed to test the dose-dependent effects of stress on naturalistic actions in experimental tasks that are representative of what participants encounter in real life. Thereby, we acknowledge that goal-directed behavior, especially in high-performance settings, implies a synergy between various perceptual, motor, and cognitive functions, which manifest themselves in observable motor behavior. Specifically, leveraging the principle of hormesis to map the effects of stress on motor behavior, requires methodological accounts to measure the dynamics of movements or actions and systematically manipulate representative tasks regarding their stress potential (Hoffmann et al., 2018; Kiefer et al., 2018; Kiefer and Martin, 2022). In this regard, virtual reality (VR) offers novel, promising research possibilities by allowing real-time tracking of body movement in space and time in representative environments. Along with other psychophysiological data under high experimental control, VR allows to systematically vary and test situational demands and their influence on performance (Giessing, 2021; Kiefer et al., 2018).

In the case of the aforementioned police example, a representative task may include the search of a building to find an armed perpetrator, to de-escalate the conflict, to rescue civilians, and to arrest the perpetrator. In this task, successful performance could be described by various behavioral aspects, e.g., situational awareness for sources of threat, choosing the appropriate use of force, the handling of the weapons, or communication. However, these aspects only refer to performance at a specific time point during an evolving critical incident and do not acknowledge that officers respond to such incidents as a team. Rather, performance should be studied as a dynamic and complex process that emerges from collective behavior (Bennell et al., 2021). A meaningful performance variable could be a value related to tactical movement, as the officers in a team are continuously challenged to move in a coordinated way to search the building, detect potential sources of threat, surround and arrest the perpetrator, while avoiding obstacles and looking after civilians. Thus, tactical movement performance requires the use of various information sources to coordinate one's own actions with respect to the ever-changing constraints in a dynamic environment, including the actions of others.

A complete hormetic assessment must then plot the performance of the individual across tasks with varying stress potential, ranging from low to high stress (Kiefer et al., 2018; Kiefer and Martin, 2022). In the police arrest task, the stress potential can be manipulated by varying the violence of the perpetrator from verbal aggression via a knife attack to shooting, or by varying the number of involved civilians. Importantly, it cannot be assumed that all individuals experience the same stress level across different stress conditions. Thus, individual stress responses need to be captured to be able to build the individual hormetic profile. In addition to emotional stress responses, physiological stress responses can help to gain a holistic picture, as emotional and physiological stress responses typically do not correlate (Campbell and Ehlert, 2012). One physiological parameter that reflects an individual's capacity to effectively organize physiological and behavioral resources in response to environmental demands is cardiac vagal control, measured by heart rate variability (HRV; Laborde et al., 2018). Specifically, in tasks involving higher levels of physical activity, when exposed to stress, higher vagal withdrawal, i.e., lower cardiac vagal control during the task, is associated with better self-regulation performance (Laborde et al., 2018).

In a practical sense, the individual hormetic profiles may not only provide information about the maximum performance levels of individuals, but may also provide more nuanced insights into their adaptability to stress. Specifically, the hormetic profiles may indicate under which stress level individuals underperform, because they are not sufficiently challenged. However, these profiles may also indicate when their capabilities are exceeded and which stress levels trigger adaptive responses in terms of maximum performance. This information can be used to personalize training environments, as it allows to identify critical training windows, in which officers perform at their maximum. For instance, the concept of pressure training proposes that physically practicing domain-specific skills under simulated stress improves performance under stress, but it has not been specified yet how much stress should be elicited (Giessing, 2021).

### 1.4. The present study

In high-performance settings, performance refers to a dynamic, complex interplay of cognitive and motor components, which manifests in motor behavior in the face of significant stress. While a large body of literature targets the mechanisms underlying the maladaptive effects of stress on performance, less is known about potential performance-enhancing effects of stress. The hormesis hypothesis provides a plausible framework to explore positive behavioral functioning in the context of stress. Leveraging the hormesis framework, we made use of VR to assess dynamic behavioral responses to varying stressors in an ecological setting, while placing a special emphasis on individual stress-response profiles to overcome non-ergodicity issues. Specifically, we aimed to test whether there is a hormetic effect of stress responses on police officers' tactical movement performance in virtual scenarios, with increasing levels of aggression by a perpetrator. We expected that low-to-moderate stress would be linked to increased tactical movement performance because with increasing stress levels officers may be more motivated and/or focused to adhere to the tactical formations, procedures, and rules. Moderate-to-high-stress levels would be associated with decreased tactical movement performance, as officers may be no longer able to adhere to the tactical formations, procedures, and rules.

**Hypothesis**. Stress and tactical movement performance exhibit hormetic, i.e., curvilinear, associations.

Importantly, the non-ergodicity issue may also apply for the hormetic curve itself. This means that individuals may not only differ in their stress response to a specific stressor, but also in the exact shape of the hormetic curve (Hill et al., 2020; Kiefer et al., 2018; Kiefer and Martin, 2022). In other words, two individuals – even with the same performance maximum – might respond, cope, and ultimately perform differently when facing the same stress dose. Individuals may differ in their response to the same stressor because of differences in personal attributes (e.g., Frenkel et al., 2018, 2019; Mosley et al., 2017, 2018), appraisals (e.g., Hase et al., 2019) and/or coping strategies (Gröpel and Mesagno, 2019). Such a lack of group-to-individual generalizability has already been shown for both protective factors (Hill et al., 2021) and load-recovery dynamics (Neumann et al., 2022). Thus, it is critical to individualize stress-performance relationships, which is why we integrated random slopes into the analysis.

## 2. Method

### 2.1. Transparency and openness

We describe our sampling plan, all data exclusions (if any), all manipulations, and all measures in the study, and we adhered to the APA's JARS-Quant methodological checklist. Data are not available due to their proprietary nature. Data were analyzed using MATLAB R2018a, R, version 4.1.1 (R Core Team, 2021), and the package *lme4*, version 1.1–29 (Bates et al., 2015). The design and analyses of the study were not preregistered.

### 2.2. Participants

A total of 37 officers (12 women) of a German riot police with a mean age of 28.8 years ($SD = 4.9$) participated in the study. Officers in the riot police were asked to participate in the study, as they would typically be the first responders – and are thus specially trained – for the type of critical incidents presented in the high-stress scenario. Officers were recruited within one riot police unit of 123 officers in total. Due to vacation, long-term sick leave, and parental leave, approximately 60 officers in this unit were available in the data collection period. Out of this pool, 40 randomly selected officers were asked to participate in the study. All 40 officers agreed to participate, but three had to drop out at short-notice due to sick leave. Participants – as a group – were representative of the "average riot police officer" and thus, showed a wide range in terms of age, work experience, and rank. On average, officers had 7.3 years ($SD = 4.7$) of working experience. None of the participants had ever shot or had been shot at on duty, but eleven officers had been required to draw their gun at least once. All participants provided written informed consent. The study was approved by the [name blinded for the review process] and performed in accordance with the declaration of Helsinki.

### 2.3. Set-up and scenarios

The current study was conducted during a training week in an obstacle-free 30 × 30 m gymnasium on police training premises, in which the Virtual Reality System BLUESUIT (RE-liON, Netherlands) was set up to create a pre-programmed training environment. BLUESUIT consists of a binocular head-mounted display (including microphone, sound effect, radio chatter), a SmartVest with sensors placed on the arms, torso and legs, a computing box (backpack style), and a tactical belt, including instrumentalized pistol, baton, pepper spray, and handcuffs, with similar weight and appearance as the originals. Sensors were wirelessly connected to reference poles to track motions and positioning in space, and the system allowed participants to see their virtualized hand- and feet movements synchronized to their actual movements.

Officers participated in intervention teams of four ($n = 7$ teams) or three ($n = 3$ teams; due to sick leave) in 3-h sessions that involved three different scenarios each. One participant reported to experience cybersickness and dropped out of the last scenario. Another participant dropped out of two last scenarios due to technical difficulties in the VR system. In each intervention team, one officer was assigned to lead the team across all scenarios, either by rank, work experience, or nomination by the group. Scenarios were designed together with an experienced police trainer to provide an increase in stress potential from one scenario to the next. Stress potential was manipulated by increasing the perpetrator's aggression, the number of perpetrators, and the number of involved civilians. Each scenario started with a simulated radio message by the police trainer to provide the officers with information on the scenario through their headset (for an overview see Table 1). In all scenarios, a role player and multiple non-playing characters (NPCs) were involved. NPCs are any characters in the virtual environment that are not synchronized to the person's behavior, but are controlled or preprogrammed by an operator. Although pre-programming the perpetrators' behavior by using NPCs would have ensured that behavior is consistent across scenarios and repeats, NPCs come at the cost of unnatural gestures and delayed responses. Thus, to allow for immediate verbal communication and physical interaction with the officers (e.g., during handcuffing), the perpetrator(s) were acted by the same male role player across all scenarios and repeats. The role player was also equipped with the VR system BLUESUIT, so that his position and actions were directly simulated in the virtual environment. To increase consistency in the role player's behavior, he was extensively trained by the police trainer following a script. Civilians in the scenarios were all NPCs with pre-programmed behavior, as they did not require verbal or physical interaction with the officers.

**Low Stress (LS) Scenario**. Officers were dispatched to a furniture store, in which an aggressive person was reported to be physically attacking people. The team started in front of the store, requiring them to enter the store and navigate through the store, to find the perpetrator outside and behind the store. In the shop, the officers encountered three civilians as non-player characters (NCPs): one man cowering next to the door and screaming, one injured woman screaming with traces of blood, and one woman running away from the perpetrator when officers crossed a trigger zone. The perpetrator was verbally aggressive, shouted at civilians, and gesticulated wildly, but carried no weapon. When clearly addressed by the officers, the perpetrator behaved cooperatively and let himself be arrested without resistance. The average duration of the scenario was 2:09 min ($SD = 0$:25 min).

**Medium Stress (MS) Scenario**. Officers were dispatched to a furniture store, in which a person was reported to attack civilians with a knife after having been repeatedly requested to leave the store. Again, the team started in the front of the store. Officers encountered five civilians as NCPs: one anxious man and a child in front of the shop with traces of blood, one woman stabbed lying on the floor in the shop with

**Table 1**
Overview of the scenario descriptions.

| Scenario | Location | Level of aggression | Number of perpetrator (s) | Number of civilians | Radio message |
|---|---|---|---|---|---|
| Low Stress | Furniture store | Verbal aggression (no weapon) | One perpetrator (cooperative) | Three civilians (two injured, one bystander) | "We got a report of a fight at a furniture store at 33 Hofer Street. Probably trespassing. A male person won't stop yelling around the store." |
| Medium Stress | Furniture store | Knife attack with an injured civilian | One perpetrator holding a knife | Five civilians (two anxious bystanders outside the shop, one bystander running out the shop, one unharmed bystander inside, one injured bystander inside the shop sitting on the floor) | "There was a fight in a furniture store – a person was asked to leave the store because they wouldn't stop yelling around. The person then suddenly shouted around and started attacking people with a knife." |
| High Stress | Furniture store | Terror attack with gun weapons, shooting still ongoing | Two perpetrators (one outside the shop, one on the second floor) | Seven civilians (one shot civilian outside the shop, three bystanders outside the shop being shot, one shot and two injured civilians inside the shop) | "There is a firearms incident at the furniture store. All we know is that a man is shooting at people with a long gun in front of the store. People have been reported shot and injured". |

blood stains, two unharmed women running away from the perpetrator when officers crossed a trigger zone. After navigating through the store, the officers encountered the perpetrator in the back room of the store. After some cross talk, the perpetrator slowly approached the officers carrying a knife in his hands. When clearly addressed by the officers, the perpetrator dropped the knife and acted according to the officers' instructions. The average duration of the scenario was 2:15 min ($SD$ = 0:38 min).

**High Stress (HS) Scenario**. Officers were dispatched to an active shooter incident in a furniture store. The team started from the back of the store, requiring them to move around it. Around the corner, they encountered the first perpetrator shooting several civilians. After shooting the first perpetrator, the team received another radio message that informed them about a second perpetrator inside the store on the second floor. Officers encountered seven civilians as NPCs: two men outside the shop, two women outside the shop running towards the officers, one shot man inside the shop, one man escaping from the second perpetrator down the stairs, and two shot woman and one woman sitting and bleeding on the first floor. After navigating through the store and walking up the stairs, officers encountered the second perpetrator in a room left to the stairs. Again, officers were required to shoot the perpetrator as lives of civilians were in immediate danger. The average duration of the scenario was 3:34 min ($SD$ = 1:05).

### 2.4. Measures

**Stress Measures.** After each scenario, participants rated their state anxiety, stress, and, mental effort they had experienced during the scenarios by using three distinctive visual-analog scales: Anxiety and stress scores ranged from 0 (*not at all anxious/stressed)* to 100 (*extremely anxious/stressed;* i.e., anxiety thermometer; Houtman and Bakker, 1989) and mental effort scores ranged from 0 (*not effortful*) to 150 (*extremely effortful; i.e.,* Rating Scale for Mental Effort [RSME]; Zijlstra, 1993; German version: Eilers et al., 1986). Single-item rating scales were used to limit the duration of interruptions during the training procedures. The rating scales have been shown to detect differences between within-person stress conditions (e.g, Giessing et al., 2019; Nibbeling et al., 2014; Nieuwenhuys et al., 2008; Renden et al., 2014, 2017).

A full ECG was continuously measured using the chest belt of the wireless heart rate monitor Zephyr BioHarness (ZephyrTM Performance Systems, USA; for reliability see Nazari et al., 2019) at a frequency of 250 Hz. It was connected through Bluetooth to the BLUESUIT system. Full ECG recordings were retrieved and visually inspected using the Kubios HRV analysis software (Biosignal Analysis and Medical Imaging Group, Kuopio, Finland). Artefacts were corrected manually (Laborde et al., 2017). Vagally mediated heart rate variability (vmHRV) as an index of self-control (Laborde et al., 2018) was calculated as the Root Mean Square of Successive Differences (RMSSD) from time domain analyses. It is deemed a reliable measure of vmHRV under ambulatory trails since it is relatively free of respiratory influences as compared to high frequency parameters (Laborde et al., 2017). Task vmHRV was assessed during the entire duration of each trial of the scenarios.

**Performance Measures.** To account for motor behavior as a dynamic and complex process and the fact that police officers are trained to respond to critical incidents as a team in a coordinated manner, we measured performance by tactical movement. In fact, tactical movement through buildings as a group is a central part of the police training curriculum (see Kleygrewe et al., 2022). Research on performance analysis in sports has recently examined variability in movements and actions using non-linear measures (e.g., entropy) in order to understand how individuals and teams vary their tactical behaviors to ever-changing constraints in dynamic environments (e.g., Silva et al., 2016). In dynamic environments such as team sports or critical police incidents, individuals are required to adjust their individual actions or movements according to the constantly emerging dynamics in the spatial-temporal relations of their team members and opponents. As a consequence, variability in actions or movements is of central importance to ensure adaptive and innovative solutions, to achieve a certain goal within environmental circumstances. It is assumed that there is an optimal amount of variability of performance, whereas periodic (high regular) or random (high variable) actions or movements are dysfunctional (Silva et al., 2016). Entropy measures describe the regularity within a time series. This means that the more often a specific point or precise sequence of point recurs, the more regular the signal is, and little new information is added with increasing time. The more new information is continuously added, the higher the entropy values become. Vice versa, lower values of entropy represent more regularity within the time series.

In the present study, sample entropy (SampEn) of each officer's velocity was calculated to quantify performance in tactical movement (cf. Kuznetsov et al., 2014; Silva et al., 2016). The velocity was derived from the displacement in the 2D spatiotemporal data of collected by the Zephyr BioHarness at a frequency of 100 Hz. Deriving the velocity creates a relatively stationary signal with an appropriate length, which is important for the analysis (Kuznetsov et al., 2014). Because optimal movement patterns tend to display an interplay between stability and flexibility in their temporal structure (e.g., Den Hartigh et al., 2015, 2021), very high SampEn values may represent too unstable patterns, while very low SampEn values may represent too much rigidity in the movement patterns.

### 2.5. Procedure

An overview of the study procedure can be found in Fig. 2. Upon arrival, participants received information about the study and filled in the informed consent. Participants were equipped with the heart rate monitor and put on the SmartVest, the headset, and computing box (BLUESUIT, RE-liON, Netherlands). After calibration of the tracking system, participants received the tactical belt with police gear. After calibration of each item, participants underwent a tutorial scenario, in which they learned to navigate through the virtual environment, walking up and down the stairs, opening doors, interacting with NCPs and using their police gear. The calibration and tutorial scenario were instructed by the police trainer and a VR operator to ensure police-specific preparation. The procedure lasted approximately 45 min.

After the tutorial scenario, the actual training session began. Officers underwent all three scenarios as an intervention team of three to four officers. For ethical reasons, scenarios were in a fixed order of increasing stress potential to avoid exposure to overwhelming stress. Immediately after each scenario, the officers filled out the questionnaire on self-reported anxiety, stress, and mental effort on a tablet. Then, the police trainer conducted a debriefing session on the team's task performance using the after-action review of the VR system. The police trainer could decide whether to have another trial of the same scenario to strengthen the learning outcome. Two teams underwent a second trial of the MS scenario and all teams underwent a second trial of the HS scenario (see Fig. 2).

After the debriefing of the last trial of the HS scenario, participants filled out a demographic questionnaire and the SmartVest and heart rate monitor were detached. Officers were thanked for participation.

### 2.6. Statistical analyses

Data on vmHRV were checked for outliers and normal distribution was tested using the Kolmogorov–Smirnov test. There were missing vmHRV data in seven scenarios across six participants due to artefacts. Outliers were winsorized ($M$ + 2 x $SD$). Variables of vmHRV were not normally distributed and thus, naturally log-transformed in line with the recommendations of Laborde et al. (2017). To enhance comprehensibility, back transformed values will be used in the Figures.

To test the effects of the stress manipulation across the scenarios, anxiety, stress, mental effort, and vmHRV in the first trial of each

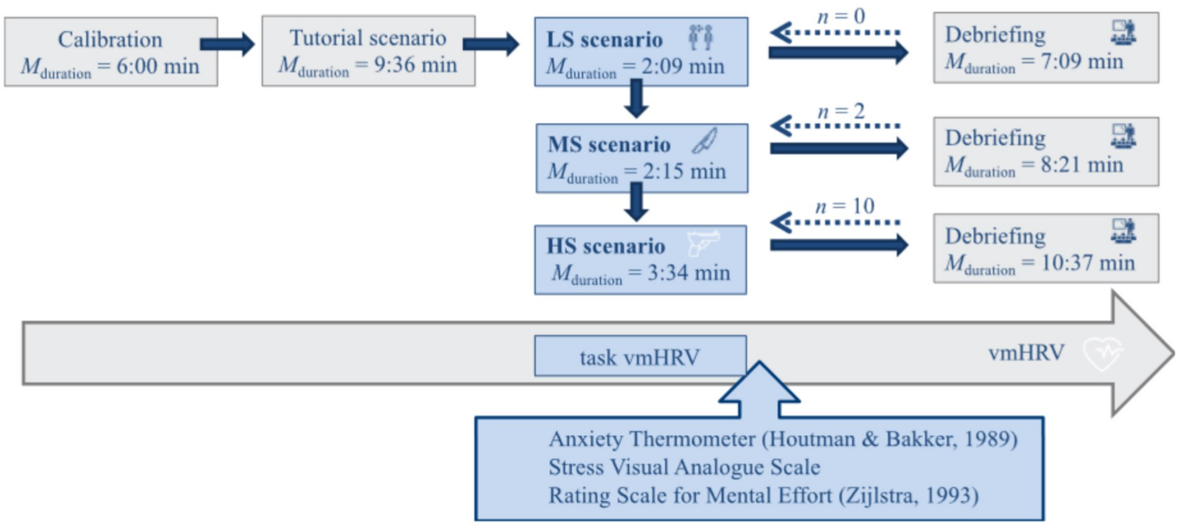


**Fig. 2.** Overview of the study procedure.
*Note.* LS = low stress, MS = medium stress, HS = high stress, vmHRV = vagally mediated heart rate variability.

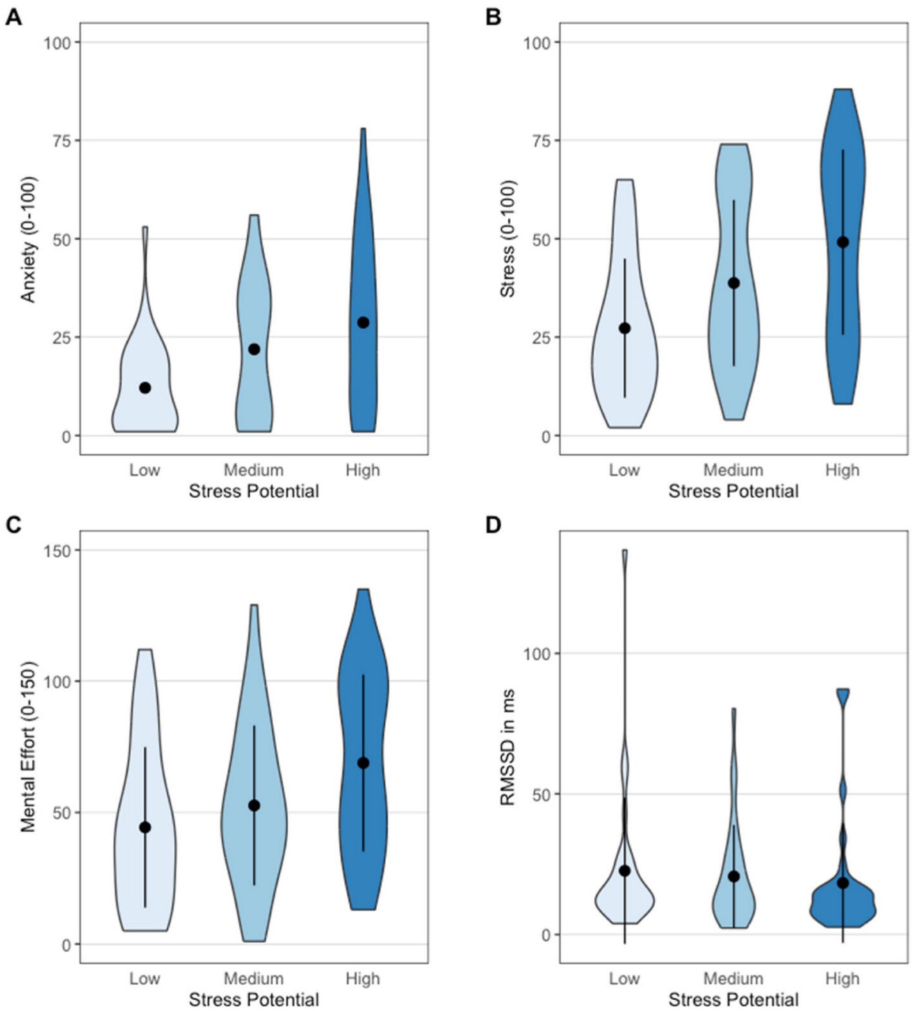


**Fig. 3.** Violin plots of stress measures in each scenario.
*Note.* The dot shows the mean value in each condition, and the error bar represents standard deviation. The width depicts the density of the distribution. Panel A: Anxiety scores. Panel B: Stress levels. Panel C: Mental effort. Panel D: Vagally mediated heart rate variability.

scenario were compared using repeated-measures ANOVAs. Given the dropout of two participants due to cybersickness and technical difficulties, the sample size for the ANOVA analyses of anxiety, stress, and mental effort was $n = 35$. For the ANOVA analysis of vmHRV, the sample size was $n = 29$ given the exclusion of additional six participants due to artefacts. Greenhouse–Geisser corrected $p$-values were reported when the assumption of sphericity was violated, as indicated by the Mauchly test. Significant main effects were further analyzed with Bonferroni corrected paired $t$-tests.

Multi-level regression models (Level 1: scenario, Level 2: participant) including linear and quadratic predictors were used to test the hypothesized quadratic relationship between performance and stress, anxiety, mental effort, and log-transformed HRV, respectively. For all models, per-participant random adjustment to the fixed intercept ("random intercept") and per-participant random adjustments to the slopes ("random slopes") were entered to allow for inter-individual differences in the shape of the hormetic curve (cf. Kiefer et al., 2018). Multicollinearity between the stress parameters and their own quadratic term was reduced through group-mean centering. Unstandardized regression coefficients (i.e., slopes) are represented by $b$ with standard errors in brackets. All $p$-values were determined with the Satterthwaite's approximation (cf. Luke, 2017), performed with the lmerTest package (version 3.1–3; Kuznetsova et al., 2017).

## 3. Results

### 3.1. Stress potential of the scenarios

The results of the ANOVA showed that anxiety significantly differed between the scenarios, $F(2, 68) = 19.54$, $p < .001$, $\eta^2p = .37$. Specifically, officers reported significantly higher anxiety in the MS ($p = .001$) and HS scenario ($p < .001$) compared to the LS scenario as well as higher anxiety in the HS scenario compared to the MS scenario ($p = .027$; see Fig. 3A). Likewise, stress significantly differed between scenarios, $F(1.71, 58.21) = 27.68$, $p < .001$, $\eta^2p = .45$. Again, officers reported significantly higher stress levels in the MS ($p < .001$) and HS scenario ($p < .001$) as well as higher stress levels in the HS scenario compared to the MS scenario ($p = .003$; see Fig. 3B). Mental effort significantly differed between scenarios, $F(1.59, 54.13) = 11.33$, $p < .001$, $\eta^2p = .25$. Officers reported significantly higher mental effort in the HS scenario compared to the LS ($p = .002$) and MS scenario ($p = .005$). However, there was no significant difference in mental effort between the LS and MS scenario ($p = .193$; see Fig. 3C). vmHRV did not significantly differ between scenarios, $F(2, 56) = 2.33$, $p = .106$, $\eta^2p = .08$ (see Fig. 3D).

### 3.2. Hormetic effect

Anxiety did not have a quadratic association with performance, $b = -0.00$ (0.00), $t(12.11) = -1.20$, $p = .255$ (see Fig. 4A). Stress did not have a quadratic association with performance, $b = 0.00$ (0.00), $t(28.00) = -0.93$, $p = .362$ (see Fig. 4B). Mental effort did not have a quadratic association with performance, $b = 0.00$ (0.00), $t(23.08) = 0.05$, $p = .961$ (see Fig. 4C). vmHRV did not have a quadratic association with performance, $b = 0.02$ (0.04), $t(7.52) = 0.37$, $p = .725$ (see Fig. 4D).

## 4. Discussion

The current study advances the understanding of goal-directed behavior in the face of different stress doses in high-performance settings. Past research focused on the maladaptive effects of high levels of stress on cognitive and motor performance (Nieuwenhuys and Oudejans, 2017). Less is known about the effects of low-to-moderate stress, under which individuals have been shown to maintain or even increase performance. We built on the hormesis framework to test the effect of different stress doses on goal-directed motor behavior in naturalistic police scenarios. Specifically, we expected a U-shaped relationship between stress and tactical movement performance, allowing interindividual variability in stress reactivity and stress-performance slopes. We followed recent calls for a pragmatic and methodological turn to investigate naturalistic actions in representative designs (Ibanez, 2022; Maselli et al., 2023). To this aim, we made use of virtual reality as an innovative technology to assess dynamic psychophysiological and behavioral responses to varying environmental stressors in naturalistic contexts. Anxiety, stress, and mental effort significantly increased with increased stress potential in the scenarios. Contradicting the hypothesis, results indicated that tactical movement performance was unrelated to

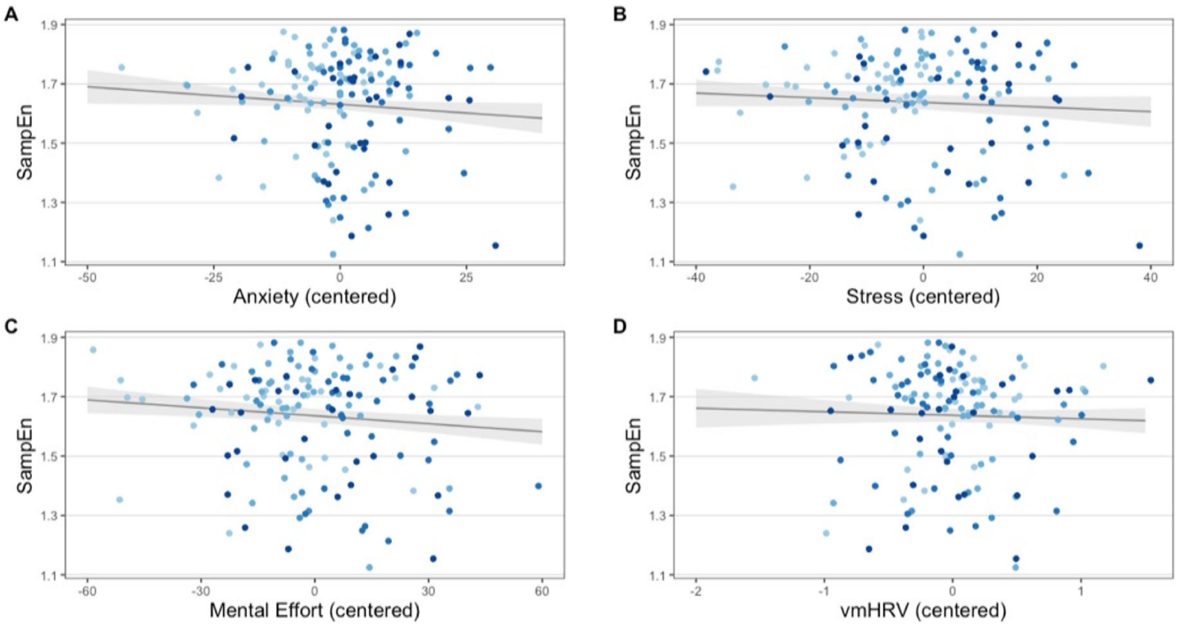


**Fig. 4.** Scatter plots of stress measures with predicted regression line.
*Note.* Circles represent data of single individuals, whereby the intensity of blue-scale filling of the circles represents the scenarios of increasing stress potential. The black line illustrates the quadratic prediction and the grey band the standard error of the regression. Panel A: Anxiety scores. Panel B: Stress levels. Panel C: Mental effort. Panel D: Vagally mediated heart rate variability.

experienced stress levels in police-specific virtual environments.

### 4.1. Theoretical implications

From a theory building standpoint, the lack of a significant effect of stress on tactical movement performance questions whether the goal-directed behavior under stress does indeed present the typical U-shape (Hardy and Parfitt, 1991; Kerr, 1985; Yerkes and Dodson, 1908). Calabrese and Baldwin (2003) reported that one of the most important criticisms against the existence of a hormetic function was the fact that no underlying mechanism(s) had been proposed to explain the presence of hormesis (Lupien et al., 2005). Similarly, we have not provided an assumed underlying mechanism for the hormetic effect of stress on tactical movement performance in the present study. Given the task demands in the present study and from an embodied-cognition perspective, we argue that performance occurs through the interplay of cognitive and motor processes (Nieuwenhuys and Oudejans, 2017; Raab, 2017; Voigt et al., 2023). Inverted U-shaped relationships between stress and cognitive processes have already been found in the literature (Domes et al., 2004; Hepler and Andre, 2021; Schilling et al., 2013). Regarding motor processes, stress has been shown to lower the excitation threshold in the cortico-spinal tract (Schutter et al., 2008) and to increase muscle tension (Coombes et al., 2009; Stins et al., 2011; for an overview see Nieuwenhuys and Oudejans, 2017). However, dose-dependent effects on the motor level remain unspecified. Thus, future research should measure dose-dependent effects of stress on the cognitive and motor level as well as their interactions (cf. Nieuwenhuys and Oudejans, 2017).

Another potential explanation for the lack of a significant effect of stress on tactical movement performance originates in the stress manipulation. It has been theorized that performance-contingent manipulations of stress, in which task errors are followed by a negative aversive consequence (e.g., pain stimulus) may motivate good performance more readily as compared to when the aversive stimulus is implemented irrespective of task performance (cf. van Peer et al., 2019; Voigt et al., 2022). Potentially, hormesis in goal-directed behavior may only be observable when the stressor motivates good performance. Thus, future research should test the effect of performance-contingent stressors on performance.

Considering dose-response profiles across various phenomena (Calabrese and Blain, 2011; Calabrese and Mattson, 2011), there are plenty of examples where there is no neat inverted-U or J-shaped profile, but some other odd shapes (e.g., a steady incline up to a peak followed by an immediate drop below baseline with the next higher dose; Calabrese, 2005). So, the exact shape and biphasic characteristics of the hormetic curve illustrated in Fig. 1 may not be representative of all biological systems or all types of stressors and may not constitute the conditions of hormesis. This might explain why the present study has failed to observe the assumed curvilinear association between stress and tactical movement performance. While testing the U-shaped relationship between toxicity and functional responses appears to be the most popular method, there are other methods to assess hormetic processes. First, dose-response features of hormesis have quantifiably similar features across various phenomena (Calabrese and Blain, 2011; López-Otín and Kroemer, 2021). In most cases of hormesis, maximum stimulatory responses at modest stimulation are no greater than 130–160% of the control, and the width of the stimulatory dose range is below a 20-fold increase from baseline (Calabrese et al., 1999). Second, the hormesis framework is used to quantify an estimate of biological adaptability, i.e., phenotypic plasticity (Calabrese and Mattson, 2011). Phenotypic plasticity is broadly defined as an environmentally based, and generally adaptive, change (Agrwala, 2001). It can be quantified as the area under the hormetic curve (Calabrese and Mattson, 2011; Kiefer et al., 2018; Kiefer and Martin, 2022; for an example in sports see Hill et al., 2020). Thus, future research should employ these other methods to test the hormetic effect of stress on motor behavior.

### 4.2. Practical implications

Given the repeated observation of cognitive-motor performance decrements under stress (e.g., Nieuwenhuys and Oudejans, 2017), many professions in high-performance settings have been interested in training interventions that are aimed at the maintenance or even improvement of performance during stressful situations (Di Nota and Huhta, 2019; Giessing, 2021; Kegelaers and Oudejans, 2022). Training interventions that involve the physical exercise of domain-specific skills under moderate levels of simulated stress have been found effective in various domains such as sports, military, and police (Low et al., 2021). These findings support the notion of the inverted-U hypothesis that training under no stress and too large doses of stress may be ineffective. Our findings extend this line of practically oriented work by examining the tactical movement performance across multiple doses of stress. While previous studies in police samples have investigated performance at one specific timepoint during the scenario, we conceptualized use-of-force incidents as a complex system that emerges from collective behaviour (cf. Bennell et al., 2021) and assessed a process parameter of performance. We found no evidence that tactical movement performance – unlike shooting, communication, and defense techniques (Arble et al., 2019; Giessing et al., 2019; Nieuwenhuys et al., 2012a,b, 2017; Renden et al., 2014, 2017; Taverniers and De Boeck, 2014) – is related to stress. Thus, the question may arise how collective variables, such as tactical movement performance, may be qualitatively different to the other skills. Several reasons could be speculated. First, the measurement over time – in contrast to measurements at one specific timepoint – and/or the conceptualization of performance as an ongoing interaction with the environment might conceal performance collapses at specific timepoints and/or of individuals. Instead, it could be that it rather emphasizes the complexity and process of performance (Bennell et al., 2021; Hoffmann et al., 2018). Thus, a person might be able to maintain overall performance under stress and evolving over time during the scenario, despite momentary performance collapses. Second, a person might be able to maintain tactical movement performance easier in high-stress situations, speculatively due to social processes. From a practical view, collective performance maintenance should be more relevant than individual performance decrements, as in most high-performance settings critical incidents are usually resolved in teams (with the exception of individual athletes). Thus, more research should target dynamic and collective performance in naturalistic environments, embracing the full complexity. Third, tactical movement performance might be trained differently and/or more frequently which allows transfer to high-stress situations (Kleygrewe et al., 2022). Future research is needed to evaluate differences in training procedures for different police skills and how they impact maintenance of these skills under stress.

### 4.3. Limitations and future research directions

Some limitations in our research methods should be noted. Results concerning vmHRV should be interpreted with caution. We did not find any significant differences in vmHRV between the scenarios, despite significant increases in anxiety, stress, and mental effort. While measurement in ambulatory settings is generally possible (Laborde et al., 2017) and other studies have successfully implemented vmHRV measures in similar settings (e.g., Brisinda et al., 2015; Linssen et al., 2022; Saus et al., 2006), this finding might be a sign that our data is too heavily distorted by biases resulting from physical activity. As a consequence, our study is mainly based on self-report, which could introduce common method biases, particularly for police officers who are reported to be resistant to report experiences of stress (Di Nota and Huhta, 2019). Indeed, officers in the present study reported rather low levels of anxiety, stress, and mental effort (see Fig. 3A–C), although both the MS and HS scenario included stressors which were rated among the top five most stressful events in police service (i.e., situations requiring use of force and killing someone in line of duty, Violanti et al., 2016). Nonetheless, it is not clear which aspects drove the stress ratings. It cannot be ruled out that participants did not only rate the stressors included in the scenarios, but also included experiences unique to the VR environment (e.g., cybersickness, potential spatial and temporal inaccuracies in the simulation) into their ratings. In a direct comparison of real-life and VR-based training, stress ratings did not significantly differ between the two settings, but mental effort was significantly higher in VR and was predicted by participants' characteristics that were suggestive of technological affinity (Kleygrewe et al., 2023). Thus, in accordance with these findings, anxiety and stress ratings in the present study may reflect experiences regarding the stressors, whereas mental effort ratings may also include additional extraneous cognitive load that comes from the novelty of the virtual environment, VR equipment, and/or VR as a training tool. Importantly, in the present study, we compared ratings across virtual conditions only, and it is unlikely that VR experiences systematically differ between the stress conditions. Additionally, the restricted range in self-reports might have biased the correlation with tactical movement performance to 0. We used single-item measures for the stress-related constructs. While common in experience sampling research in the field due to practical constraints, it may introduce reliability concerns (Nunnally, 1978). Given the limitations in self-report, future research should continue to use multimethod approaches combining psychological and biological assessment to evaluate the impact of stress on goal-directed behavior, while advancing in methods to control for the effects of physical activity.

Concerning the study design, the fixed order of scenarios and the configuration of the LS scenario as reference might have biased our results. Officers underwent the scenarios in escalating order from low to high stress and police trainers were allowed to give feedback regarding officers' performance after each scenario and let officers repeat scenarios. While this procedure was necessary to ensure officers' psychological safety during the study, participants might have realized that scenarios increase in their stress potential and thus, this procedure might have led to demand effects on the self-report measures. Additionally, experiences in previous scenarios might have resulted in unwanted learning or carry-over effects in the latter scenarios (see Hill et al., 2020). For instance, learning experiences in the LS and MS scenario might have improved performance in the HS scenario due to knowledge or skill acquisition or positive experiences in the LS scenario might have changed cognitive appraisal processes about the demands and their coping resources in the upcoming scenarios, resulting in lower stress levels (Lazarus and Folkman, 1984). Therefore, future research should ensure to employ study design with counter-balanced order of stress conditions to eliminate demand, learning or habituation effects, while considering psychological safety in high-stress contexts.

Further, the respective scenarios might have not represented the desired hormetic zones. We aimed to conceptualize the LS scenario to represent baseline functioning, the MS scenario to fall into the hormetic zone, and the HS scenario to be beyond the threshold (see Fig. 1), while considering interindividual differences in stress reactivity and placing individuals on the hormetic curve based on their stress responses. Although we observed intraindividual variability in stress responses to the scenarios (see Fig. 3), we might have failed to elicit the full range of stress responses falling into the desired zones (i.e., baseline, hormetic zone, and toxic zone beyond the threshold). This might be particularly true for the LS scenario. It is still a theoretical debate how to define baseline functioning. The performance variable in the present study was a composite score of goal-directed behavior in a specific task context. In the attempt to keep the task across the scenarios as similar as possible (i.e., move through the building to find a suspect), the presence of a suspect might have already shifted officers from baseline functioning to slightly increased stress responses. Speculatively, an additional baseline (no-stress) scenario requiring officers to only patrol the building without the presence of a suspect might have more closely represent baseline functioning, allowing performance increases in the typical range of 30–60% above baseline functioning. Alternatively, it may not be possible to measure task-relevant behavior in the absence of any stress dose. For instance, the rate of perceived exertion starts at 6 (i.e., 60 bpm) for rest or baseline functioning (Borg, 1982), as below this value there is hardly any physical activity. Thus, future research should follow the recommendation to implement a larger variation of doses. Implementing three scenarios represents the minimum dose variation, but more comprehensive and nuanced profiles require at least five doses (cf. Calabrese, 2005). Given the previously discussed idiosyncrasy of dose-response profiles, these more high-resolution profiles may enable researchers to include very small doses serving as a baseline and identify a detailed hormetic zone. In relation to the selected stress scenarios, other behavioral and physiological parameters (e.g., kinematic measures) as well as different types of stressors could be selected to construct more reliable and informative profiles (Kiefer and Martin, 2022).

## 5. Conclusion

In high-performance settings, individuals often need to maintain goal-directed behavior while interacting with stressors. Leveraging the hormesis framework, we attempted to understand whether dose-dependent effects of stress may explain maintenance or increase in cognitive-motor performance under stress. Despite increasing empirical evidence of hormesis in psychological and cognitive functioning, officers' tactical movement performance was unrelated to perceived stress in virtual police scenarios of escalating stress potential. Our study provides insights into how dose-response profiles may be constructed for future studies on hormesis in motor behavior. This can guide future work on enhancing training conditions for high-risk performance occupations.

## Author note

We have no known conflict of interest to disclose.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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