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Real-time Imaging of Stress-induced Cardiac Autonomic Adaptation During Realistic Force-on-force Police Scenarios

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Abstract Operational stress is a complex matter. It requires a better understanding based on scientific knowledge of the psychophysiology of stress to improve training methods for officer's survival and prevention of post-traumatic stress disorders. This study aimed to assess the reliability and sensitivity of heart rate and of heart rate variability (HRV) as possible objective methods to quantify police operational stress (OS) in the real world and to differentiate the contribution of overlapping physical stress (PhS) during realistic training scenarios. 12-lead ECG of 113 police officers (POs) were continuously monitored during rest, daily activity (control state), and during 172 realistic tactical training scenarios requiring the use of force and/or of shooting firearms (OS, with or without associated PhS). Baseline physiological and psychological measurements were collected on the days of the training session. POs behavior and tactical outcome were rated by police instructors and documented with multiple video cameras. Real-time imaging of tactical stress was tempted with time-varying (TV) spectral HRV analysis (HRVa). Quantitative estimates of time-domain (TD), frequency-domain (FD), and nonlinear HRV parameters were computed from standard (300 and 120 seconds) and very short-term (60 and 30 seconds) intervals. The study was approved by a local Institutional Review Board. TV spectral HRVa provided dynamic imaging of transient cardiac autonomic adaptation induced by OS and/or PhS. Quantitative estimation of the majority of TD and FD HRV parameters were not significantly affected by shortening the length of the explored time-segments from 300 to 30 seconds, as demonstrated by the intraclass correlation coefficient analysis (> 0.70). Discrimination analysis of HRV parameters allowed a differentiation between rest and stress conditions and between mental and physical stress. HRVa provides dynamic imaging and quantification of transient stress-induced autonomic adaptation in police officers during realistic tactical training scenarios.

Keywords Operational stress · Autonomic nervous system · Heart rate variability · Very short-term analysis · Realistic tactical training

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Introduction

Stress is widely investigated in psychophysiology laboratories, taking into account the role of the autonomic nervous system (ANS) to adapt to bodily demands under different conditions. ANS also plays an important role keeping physiological balance, through adjustments of cardiorespiratory function under acute psychological stress and emotions (Delaney & Brodie, 2000; Holly et al., 1997; Kreibig, 2007; Orsila et al., 2008; Pagani et al., 1991; Salahuddin et al., 2007; Shapiro et al., 2000; Stemmler et al., 2007). Although cardiac autonomic response to real-life stress has been investigated in humans (Angeles Pico-Alfonso et al. 2007; Lucini et al., 2002; Lucini et al., 2005; Melillo et al., 2011; Schubert et al., 2009; Sgoifo et al., 2003), less is known about ANS adaptation to police operational stress (OS). ANS adaptation is a complex interplay of cognitive, emotional, behavioral changes, and autonomic reactions, which is difficult to quantify even in the controlled laboratory environment. On the other hand, although it is increasingly recognized that survival stress reactions, induced by a deadly force confrontation, might affect operational efficacy (Artwohl & Christensen, 1997), objective methods to quantify tactical stress are still lacking. Since a better understanding of the psychophysiology of tactical stress might improve training methods for officer survival and prevention of post-traumatic stress disorders, "street combat" experiences of police instructors and knowledge in psychophysiology of human stress reactions must be integrated (Fenici et al., 2011).

Preliminary research correlating the intensity of survival stress with the easily measurable physiologic parameter heart rate (HR) was useful to understand how realistic force-on-force training helps prepare officers to deal with real-life operational tasks (Fenici, 1999; Grossman & Christensen, 2004; Grossman & Siddle, 1998; Massad Ayoob, 1986; Siddle, 1995; Siddle, 1999). However, the results of later studies, which monitored HR during realistic tactical training in high stress tactical scenarios, including force-on-force scenarios, evidenced that the absolute value of HR maximum peak achieved is often uncorrelated to operational efficacy (Fenici, 1999a, 1999b; Fenici & Brisinda, 2002, Fenici and Brisinda 2004; Grossman & Christensen 2004; Kemp & Dietz, 2008; Meyerhoff et al., 2004). At the Federal Law Enforcement Training Center (FLETC), officers who failed during a chase or a gunfight reached lower HR than the successful (Meyerhoff et al., 2004). In the Advanced Law Enforcement Rapid Response Training (ALERRT) study, there was no significant correlation between the amount of experience or training of officers and average or maximum HR achieved during force-on-force (Kemp & Diets 2008)

In summary, previous experimental evidence suggests that absolute values of HR cannot be assumed as a univocal index to quantify individual stress, nor to predict individual tactical efficiency under stress. On the other hand, HR is the only physiological parameter that can be easily monitored during dynamic action and through the analysis of its variability [HRV; a physiologic phenomenon resultant from the dynamic modulation of HR by the interaction of the sympathetic (SNS) and parasympathetic (PNS) nervous systems activity], it is possible to study the dynamics of stress-induced changes of cardiac autonomic modulation (Berntson et al., 1997; Billman, 2011; Braune & Geisenorfer 1995; Fox et al., 2007; Fox et al., 2008; Günther et al. 2010; Lahiri et al., 2008; Lombardi, 2002; Lombardi & Stein, 2011; Montano et al., 2009; Pagani et al. 1986; Perini & Veicsteinas, 2003; Stein et al., 2005; Sztajzel, 2004; Task Force of The European Society of Cardiology and The North American Society of Pacing and Heart rate Variability Standards of Measurement et al. 1996; Tarvainen et al., 2002; Tarvainen et al., 2006).

HRVa is increasingly used to quantify emotional response in social and psychopathological processes, in both the laboratory and in real life situations, (Appelhans & Luecken, 2006; Kreibig et al., 2007; Melillo et al., 2011; Schubert et al., 2009; Sgoifo et al., 2003; Stemmler, 2004; Stemmler et al., 2007). It might prove be a powerful, noninvasive tool to explore dynamic interactions between physiological, mental, emotional, and behavioral processes, since changes in heart rhythms affect not only cardiac function, but also the brain's ability to process information for decision-making and problem-solving (McCraty, 2002).

In general, three main HRV adaptations to acute stress have been described in laboratory studies: 1) a significant enhancement of HR indicating a shift toward sympathetic predominance, which is also evidenced by an increase in skin conductance and a decrease in skin temperature (Salahuddin & Kim, 2006), 2) enhancement of the Low Frequency (LF) component with consequent increases of the LF/High Frequency (HF) ratio (Orsila et al., 2008; Salahuddin et al., 2007), and 3) reduction of total power (RR variance), which might be partially due to depression of the HF component due to concomitant vagal withdrawal (Garde et al., 2002; Montano et al., 2009). It was also shown that additional stress (e.g., induced by painful stimulation during mental stress) increases HR without significant changes of HRV parameters (Terkelsen et al., 2005).

A recent meta-analytic review of research combining neuroimaging and HRVa has shown that, "HRV may serve as a proxy for 'vertical integration' of the brain mechanisms that guide flexible control over behavior with peripheral physiology" prior to threat, which prepares the organism for appropriate action (Thayer et al., 2012, p. 747). However, very little is known about the use of HRVa to study tactical stress reactions. Preliminary results have shown that conventional HRVa parameters calculated from long (24hours) and/or short (5minutes) time intervals are not adequate to assess ANS adaptation to acute tactical stress (Fenici & Brisinda, 2008a, 2008b). This suggests that to image acute changes of HRV spectral density during non-stationary events (such as acute stress reactions) beat-to-beat spectral HRVa with time-frequency and time-varying methods (Mainardi et al., 2002; Martinmäki & Rusko, 2008; Petrucci et al., 1996; Tarvainen et al., 2006) would be needed (Fenici et al., 2011). Alternatively, one has to rely on very-short term (VST) HRVa (Brisinda et al., 2011; McNames & Aboy 2000; Salahuddin et al., 2007; Smith et al., 2013; Thong et al., 2003), which has been used for clinical applications (Fujiwara et al., 2007; Karp et al., 2009), but has not been validated to assess police stress.

In this prospective study we have combined time-varying and short-term HRVa in order to evaluate the possible efficacy of HRVa as a method for real-time assessment of police OS and to differentiate the contribution of overlapping mental and physical stress (PhS), occurring during realistic training with force-on-force scenarios. Additionally, possible correlation between objective indices of stress (i.e., alteration of HRVa parameters) and operational efficiency was evaluated.

Methods

Volunteer police officers were monitored during normal daily activity (control state) and during different kinds of realistic tactical training scenarios requiring the use of force and/or of shooting firearms (operational stress). The study was approved by the local review board and was performed in accordance with the ethical standards of the 1964 Declaration of Helsinki. All subjects gave informed consent prior to their inclusion in the study.

Subjects

A total of 113 participants, all active sworn police officers from different police agencies, volunteered for the study. The demographics of participants are summarized in Table 1. Although there was a prevalence of males (93 %), the population was otherwise homogeneous for age and level of professional experience (average 13.6 years spent serving on the force). Baseline physiological and psychological measurements were collected from the participating officers on the days of the training session. Health status of all participants was determined following screening of medical records, a clinical interview, a complete physical examination, blood pressure measurement, and rest ECG and effort ECG recordings. The subjects did not take any medication and were instructed to avoid smoking and consuming any caffeine- or alcohol-containing beverages in the 24h period before the training session.

Scenarios

All measurements were performed during realistic tactical training in three different police academies. Four scenarios were designed to simulate as closely as possible real police calls that officers would receive on duty to investigate suspected crimes (Table 2). The purpose of the scenario training was to challenge officers to practice the types of duties they would be required to perform under the pressure of a real-life police call. In the scenarios, the officers and trained role-players were armed with their service firearms, but these were modified to safely impede chambering of live rounds and to allow efficient cycling and firing of special ammunitions (Simunitions® or Airmunitions), which eject special paint bullets instead of real bullets. The four kinds of scenarios were designed based on real-life operational experiences of police instructors. The events in each scenario occurred in such a way as to induce different levels of stress (Table 2), which functioned to objectively test: Attention, communication, cover of the partner, suspect control and handcuffing technique, and appropriate use of non-lethal and lethal force, when required. The level of stress induced by each tactical skill had been previously tested with HR monitoring in our laboratory.

Before each scenario, officers went through a "briefing" procedure in which they were informed about the nature of the task, as they would be in a real police call. At the end, through a debriefing session, subjective reporting was compared with objective individual behavior provided by video recordings taken during the scenario. A total of 172 scenarios were analyzed for this study. At the end of each training session the instructors completed an evaluation, which scored the participants' tactical performance in the scenarios.

Table 1 Demographics of study population

	Male			Female		
		105			8	
	Mean	*SD*	*Range*	*Mean*	*SD*	*Range*
Age (*y*)	33,6	5,1	24-44	33,6	3,6	28-39
Duty (*y*)	13,6	5,2	4-24	13,6	3,6	8-19

Table 2 Description of tactical tasks

Scenarios	
Call for domestic violence	*Medium Stress*
Call for a robbery	*High Stress*
Building search	*High Stress*
Car chase and suspect stop	*High Stress*

Psychological Assessment

Anxiety was assessed with the State-Trait Anxiety Inventory-Trait (STAI-T). The STAI-T is a 20-item self-report measure of anxiety proneness requiring participants to rate their frequency of anxiety symptoms on a four-point Likert-type scale. Nine items were reverse scored. According to clinical practice, the cut-off score for anxiety screening is 40 (Spielberger et al., 1983). Depression was assessed with Zung's self-rating depression scale (SDS), which is a short self-administered 20 item survey that rates the affective, psychological, and somatic symptoms associated with depression (abnormal score > 50) (Zung 1965). Both questionnaires were administrated before the onset of the training session. Subjective stress perceptions and feelings of fear and/or anger during tactical tasks was rated with a questionnaire (scale 1-10), administered immediately after the end of each scenario.

Physiological Assessment

ECG Recordings

After obtaining written consent, all recordings were performed with a 12-lead ECG Holter system (H-Scribe-Mortara-Rangoni Instruments). ECG recording was started at least one hour before each training session and ended at least one hour after. Since factors, such as circadian rhythm, body position, activity level prior to recording, medication, verbalization, and breathing condition may influence the HRV, special precautions were taken to maintain similar condition in all experiments, such as performing the training session at a similar time of day (usually in the mid-late morning) and having the resting basal recordings after an adaptation time of at least 15 minutes.

Heart Rate Variability Analysis

Raw ECG data were pre-analyzed with the Mortara Holter system (v 4.35), and edited to manually remove technical artifacts (muscle or movement noise inducing wrong detection of the QRS complex) and/or physiological artifacts (e.g., arrhythmic events) before HRVa. Two scientists independently reviewed and corrected the QRS detection. The fraction of total RR intervals labeled as normal-to-normal (NN) intervals was computed as the NN/RR ratio. This ratio has been used as a measure of data reliability, with the purpose to exclude records with a ratio less than a 90 % threshold.

Raw ECG data (Fig. 1A) was then extracted from the Holter recording with a custom software routine and analyzed with a time-varying (TV) HRVa software (Kubios 2.0 beta 4, release 2007), which provided a general overview of instantaneous beat-to-beat changes of HRV spectral pattern along the whole recording period (Fig. 1B). In the Kubios software, the time-varying spectrum is estimated either by using the moving window Fast Fourier Transform (FFT), which is also known as the spectrogram method, or with the Kalman smoother algorithm (Tarvainen et al., 2006). The Kalman smoother method was used in this study because it provides better resolution than the spectrogram (Tarvainen et al., 2004).

In all subjects, TV HRVa was carried out first in order to have an overall real-time imaging of dynamic HRV changes throughout the whole monitoring period (Fig. 2). Thereafter, quantitative HRV parameters were calculated with the Kubios HRV software (v 2.1) (Niskanen et al., 2004; Tarvainen et al., 2002) from multiple RR segments

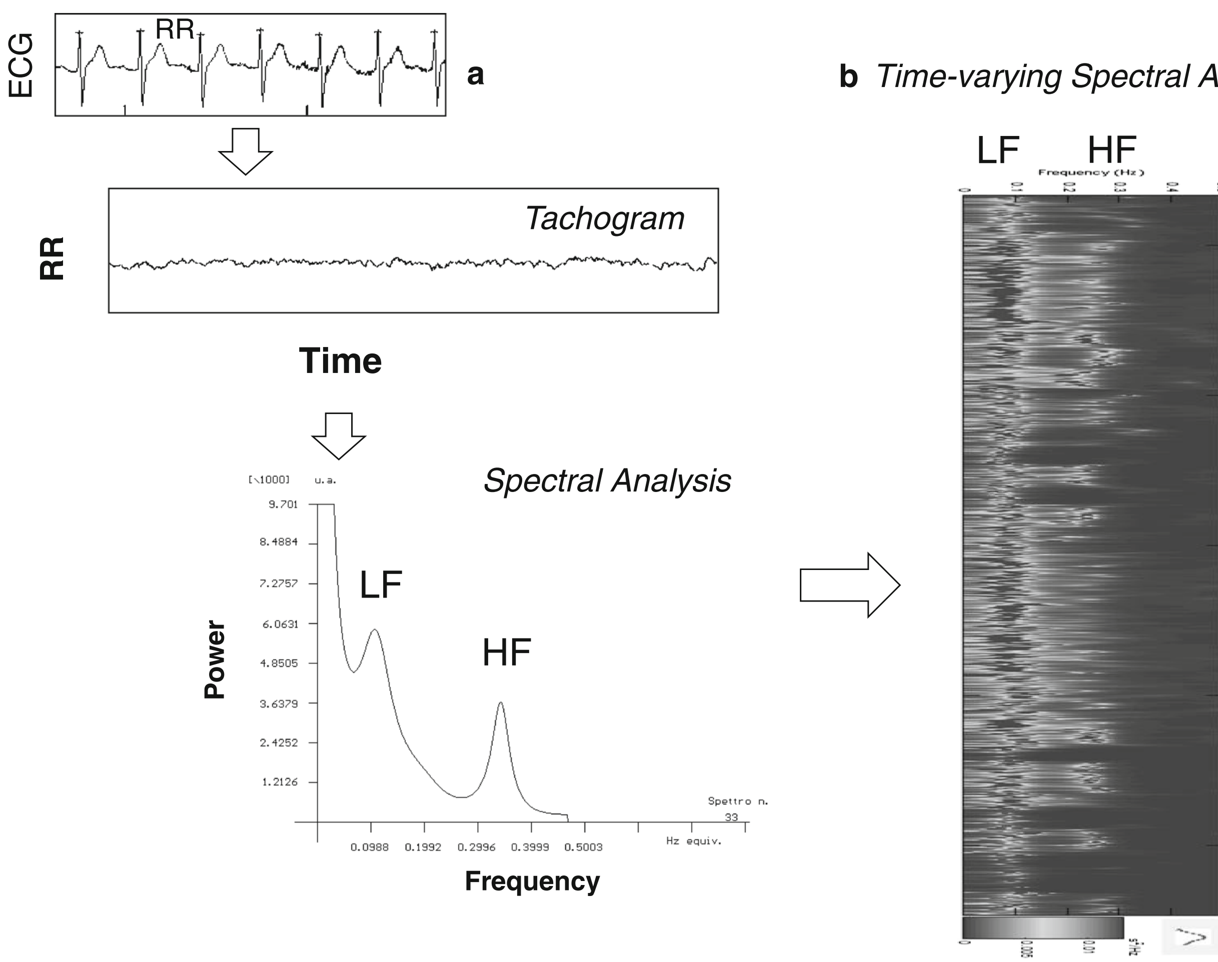

Fig. 1 Sequence of signal processing for time-varying spectral analysis of heart rate variability. (LF: low frequency; HF high frequency)

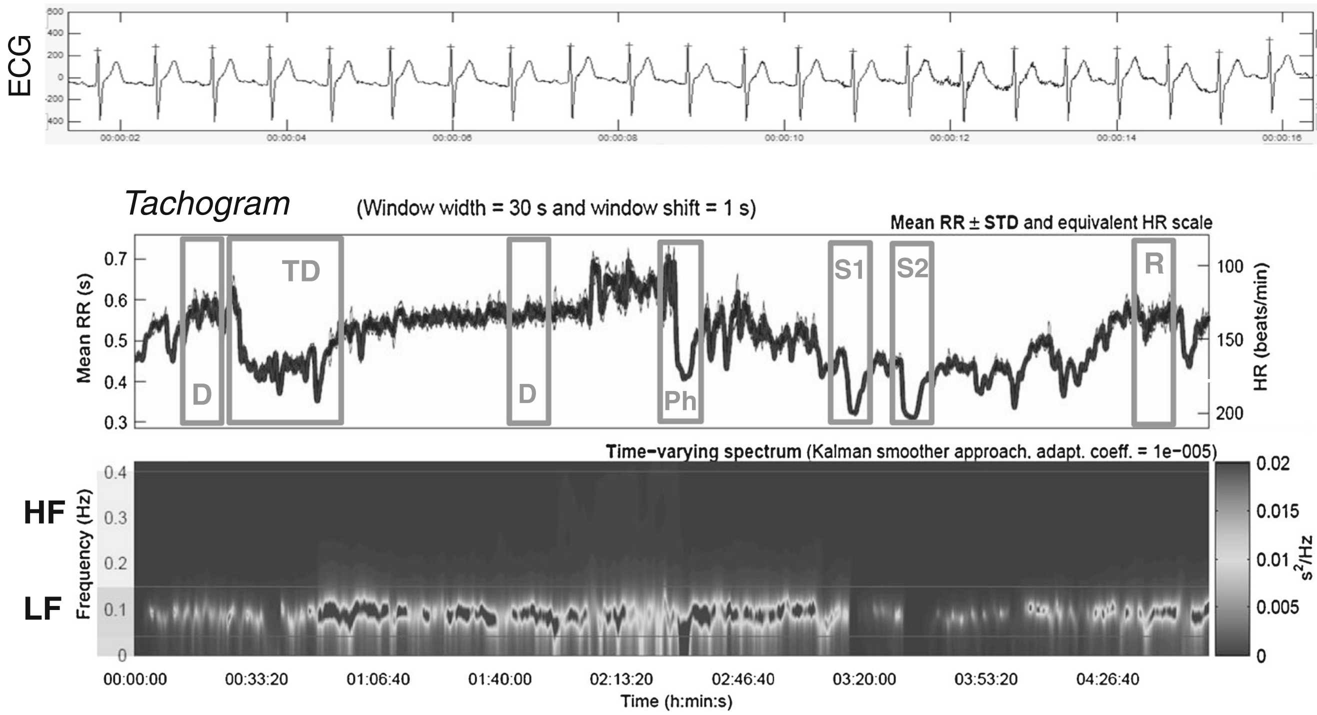

Fig. 2 Example of investigational protocol. Boxes on the tachogram indicate different conditions: daily activity (D); Tueller drill (TuD); physical effort (Ph); high stress scenarios (S1 and S2); recovery (R). Time-varying spectrum evidences significant changes of the LF component in the different conditions of the study

(of 30, 60, 120 and 300 seconds), which were selected at critical instances of the scenarios' dynamicity based on the spectral imaging provided by the preliminary TV analysis. HRV parameters were calculated in the time domain (TD), in the frequency domain (FD), and with non-linear methods. All calculated HRV features are summarized and explained in Table 3. The arbitrary criteria chosen to optimize the selection of the time-windows used for calculation were: 1) at rest, the highest possible "stationarity" of the RR signal (defined as the absence of arrhythmias and of any kind of artifacts in visual analysis of corresponding ECG recordings); 2) under stress, the measurements were centered on the maximum peak of heart rate; 3) for spectral analysis, the exploring window was adjusted, which also looked for the best coherence among spectral output obtained with the FFT and autoregressive (AR) models. In the FD, the LF/HF ratio, calculated from LF and HF in normalized units, was accepted as an index of sympathovagal interaction adequate to explore autonomic modulation (Lombardi & Stein, 2011; Montano et al., 2009).

Blood Pressure

Blood pressure measurements were performed manually with aneroid sphygmomanometer, according to clinical standards, by applying the cuff to the right upper arm.

Statistical Analysis

Mean, standard deviation, median, and 25th and 75th percentiles were calculated to describe the distribution of HRV features during stress and rest conditions. To investigate the statistical significance of features' variation within each subject, the Wilcoxon signed rank test was used. For the same parameters, the correlation was assessed using Spearman's correlation test. All statistical calculations were performed with SPSS software (v 13.0) (SPSS Inc., Chicago, Illinois).

Agreement between measurements obtained from the 300-, 120-, 60- and 30-second recordings was determined by calculating the intraclass correlation coefficient (ICC). Various categories of reliability are based on the ICC. An ICC > 0.8 is usually regarded as good to excellent reliability, whereas an ICC between 0.6 and 0.8 may be taken to represent substantial reliability (Baumgartner & Chung, 2001; Pinna et al., 2007). Discriminant Analysis (DA) (Addinsoft XLSTAT, v 2013.4.07) (Fisher, 1936; Huberty, 1994) was used to evaluate if HRV parameters were adequate to provide a separation between stress and rest phases during each training session. Two models of DA are used depending on a basic assumption. If the covariance matrices are assumed to be identical, linear DA is used. If, on the contrary, it is assumed that the covariance matrices differ in at least two groups, then the quadratic model is used. The

Table 3 Description of heart rate variability parameters

	Parameter	Units	Description
Time domain	RR mean	*ms*	Mean of RR intervals
	SDNN	*ms*	Standard deviation of RR intervals
	HR mean	*1/min*	Mean heart rate
	HR SD	*1/min*	Standard deviation of instantaneous heart rate
	RMSSD	*ms*	Square root of the mean squared differences between successive RR intervals
	NN50		Number of successive RR interval pairs that differ more than 50 ms
	pNN50	%	NN50 divided by the total number of RR intervals
	HRV triangular index		Integral of the RR interval divided by the height of the histogram
	TINN	*ms*	Baseline witdth of the RR interval histogram
Frequency domain	Peak frequency	*Hz*	VLF, LF and HF band peak frequencies
	Absolute power	ms^2	Absolute power of VLF, LF and HF bands
	Relative power	%	Relative power of VLF, LF and HF bands
	Normalized power	*n.u.*	Powers of LF and HF bands in normalized units
			LF (n.u.)=LF (ms^2)/[(total power (ms^2) - VLF(ms^2)]
			HF (n.u.)=HF (ms^2)/[(total power (ms^2) - VLF(ms^2)]
	LF/HF		Ratio between LF and HF band powers
Nonlinear	SD1, SD2	*ms*	Standard deviation of the Poincarè plot perpendicular to (SD1) and along (SD2) the line of identity
	ApEn		Approximated entropy
	Sampen		Sample entropy
	D2		Correlation dimension
	DFA		Detrended fluctuation analysis
	$\alpha 1$		Short term fluctuation slope
	$\alpha 2$		Long term fluctuation slope
	RPA		Recurrence plot analysis:
	Lmean	*beats*	Mean line length
	Lmax	*beats*	Maximum line length
	REC	%	Recurrence rate
	DET	%	Determinism
	ShanEn		Shannon entropy

Box test is used to test this hypothesis (the Bartlett approximation enables a χ^2 distribution to be used for the test). We start with linear analysis then, and depending on the results from the Box test, carry out quadratic analysis if required. DA searches for linear combinations of the input features that can provide an adequate separation between two classes (in this study, operational stress and rest daily activity). The discriminant functions used by linear DA are built up as a linear combination of the variables that seek to maximize the differences between the classes (Krzanowski, 2000; Melillo et al., 2011). The classification accuracy of the method is defined as the ability to discriminate between the two investigated situations. In a subset of subjects, DA was also used to attempt selective separation between mental and physical stress.

Results

Several officers were involved in multiple scenarios of different stress intensity. Therefore, in order to optimize statistical analysis on a homogeneous dataset, only data of one single active scenario per officer was used for this study. Data of six officers were excluded because they were playing the role of suspects.

Psychological Assessment

The results of the psychological assessment demonstrated that 93 % of the participating officers were normal. On the basis of the cut-off levels only eight officers (three borderlines) had positive scores of mild anxiety and one of them also had mild depression (values were close to the lower limits of the respective scales). For the average subjective stress perception, feelings of fear and/or anger during the scenarios were rated as above 7/10. However, several officers refused to complete the questionnaire. Therefore, this finding may be underestimated because of resistance to accept and/or report personal stress and other feelings by some of the participants.

Physiological Assessment

In general, it was observed that police officers are prone to have enhanced adrenergic tone at rest when dealing with and/or preparing for a realistic training session, as demonstrated by basal values of heart rate and blood pressure higher than normal limits (average SBP 140 ± 15 and DBP 92 ± 9.5 mmHg). The 12-lead ECG recording was useful to define the optimal positioning of electrodes in order to minimize artifacts due to muscle activity, respiration, and perspiration, and to have the highest possible choice to select a noise-free channel to use for HRVa. In this way none of the records were excluded because NN/RR ratio was always higher than 90%.

An example of step-by-step real-time imaging of stress-induced changes of autonomic modulation provided by TV HRVa of a realistic training session is shown in Fig. 3, where it is evident that operational stress of different intensities [Tueller drill (TuD) versus shooting scenario (S)] induced completely different changes of autonomic modulation of the heart rate.

Table 4 summarizes the descriptive statistics of selected linear and nonlinear (very) short-term HRV parameters of the enrolled subjects and how they varied under operational stress compared with the rest condition. Most HRV features (with the exception of HF%, LF/HF and RPadet) showed highly significant variations during OS as compared with normal daily activity (< .0001). In order to minimize errors in the evaluation of transient variations induced by short–term bursts

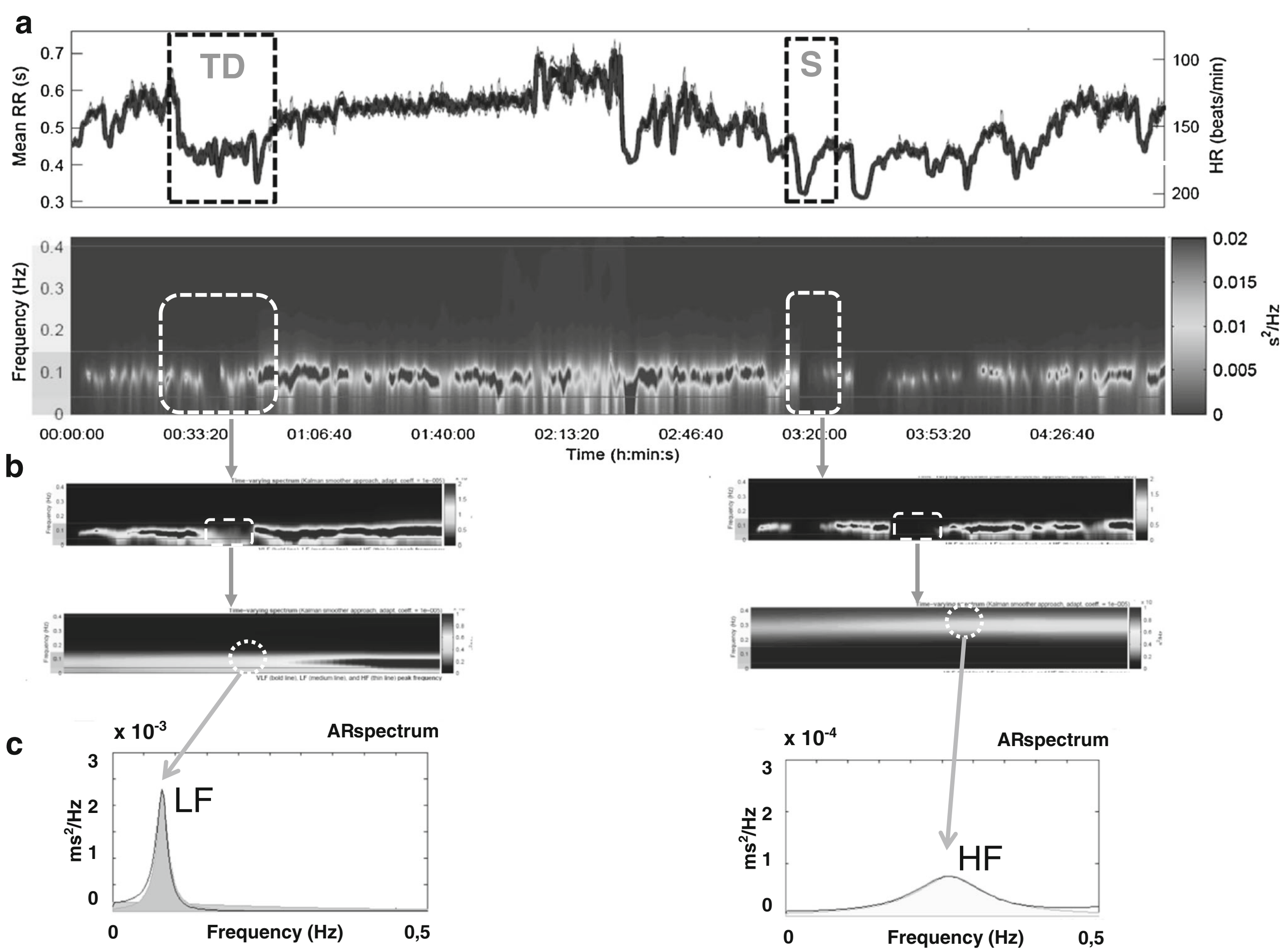

Fig. 3 Example of time-varying HRV analysis during realistic training (same case as in fig. 2). Progressively zooming on two different situations with different intensity of stress reaction, a Tueller drill (TuD) and an active shooting incident (S), [both identified by dashed squares onto the tachogram (**a**) and onto the TV strips (**b**)], provides evidence of opposite autonomic modulation, being the LF (sympathetic) component prevalent in the TD and HF (vagal) component during the shooting (see power spectra in **c**)

Table 4 Descriptive statistics of HRV parameters during normal daily activity (rest) and under operational stress (scenarios)

		REST					SCENARIOS					DIFFERENCES SCENARIOS - REST					
		Mean	*SD*	*25th*	*Median*	*75th*	*Mean*	*SD*	*25th*	*Median*	*75th*	*Mean*	*SD*	*25th*	*Median*	*75th*	*p-value* <
Time domain	*RR mean*	767,6	136,4	681,2	744,3	841,1	433,2	76,3	375,0	418,0	469,5	-334,4	-60,1	-306,2	-326,3	-371,7	*1,0E-05*
	SDNN	40,3	11,9	31,4	41,2	47,9	13,3	8,3	7,2	11,6	18,6	-26,9	-3,6	-24,2	-29,6	-29,3	*1,0E-05*
	HR mean	80,9	14,1	71,6	81,1	88,5	142,8	22,4	128,2	143,9	160,1	61,9	8,3	56,6	62,7	71,6	*1,0E-05*
	RMSSD	30,0	12,8	21,1	27,3	38,7	11,4	6,6	6,3	9,6	15,3	-18,6	-6,2	-14,9	-17,7	-23,5	*1,0E-05*
	SDNN/RMSSD	1,4	0,4	1,2	1,4	1,6	1,2	0,5	0,8	1,0	1,7	-0,2	0,1	-0,4	-0,4	0,0	*5,0E-04*
	NN50	8,3	7,6	2,0	6,0	14,0	1,7	3,5	0,0	0,0	2,0	-6,6	-4,0	-2,0	-6,0	-12,0	*1,0E-05*
	pNN50	11,7	12,0	2,5	6,9	17,8	1,3	2,6	0,0	0,0	1,3	-10,4	-9,3	-2,5	-6,9	-16,5	*1,0E-05*
Frequency domain*	*TP* ms^2	1700,5	912,6	945,0	1622,8	2241,3	224,3	431,1	24,5	79,9	225,8	-1476,2	-481,4	-920,6	-1542,8	-2015,5	*1,0E-05*
	VLF ms^2	149,4	143,2	63,3	106,9	188,9	36,9	64,5	3,9	14,0	35,8	-112,5	-78,7	-59,4	-92,9	-153,0	*1,0E-05*
	LF ms^2	1166,5	661,9	685,7	1097,4	1593,6	145,3	348,1	13,0	42,1	128,6	-1021,2	-313,8	-672,7	-1055,3	-1465,0	*1,0E-05*
	HF ms^2	383,9	332,9	138,5	257,4	569,3	42,0	80,5	5,5	12,8	46,3	-341,9	-252,3	-133,0	-244,6	-523,0	*1,0E-05*
	VLF%	8,5	5,1	5,0	7,1	10,3	20,7	15,1	10,1	17,9	24,9	12,2	9,9	5,1	10,8	14,6	*1,0E-05*
	LF%	68,8	14,3	60,2	71,7	78,7	54,1	17,9	43,3	54,7	67,3	-14,7	3,6	-16,8	-17,1	-11,3	*1,0E-05*
	HF%	22,6	14,4	12,3	19,4	29,2	25,0	18,5	10,3	19,4	36,3	2,4	4,1	-2,1	0,0	7,1	*n.s.*
	LF n.u.	75,3	15,2	66,9	79,3	85,9	69,3	19,5	57,7	74,3	84,9	-6,0	4,3	-9,2	-5,0	-0,9	*0,05*
	HF n.u.	24,6	15,2	14,1	20,7	33,1	30,5	19,4	15,0	25,3	42,3	5,8	4,2	1,0	4,7	9,2	*0,05*
	LF/HF	4,7	3,5	2,0	3,8	5,9	3,9	3,2	1,4	2,9	5,5	-0,8	-0,3	-0,6	-0,9	-0,5	*n.s.*
Non linear	*SD1/SD2*	0,4	0,2	0,3	0,4	0,5	0,6	0,3	0,3	0,6	0,8	0,2	0,1	0,0	0,2	0,3	*1,0E-05*
	SD1	21,4	9,1	15,0	19,4	27,6	8,1	4,7	4,4	6,8	10,8	-13,3	-4,4	-10,6	-12,6	-16,7	*1,0E-05*
	SD2	52,3	15,8	41,9	53,9	63,2	16,5	11,3	8,6	13,7	21,6	-35,8	-4,5	-33,2	-40,2	-41,6	*1,0E-05*
	RPlmean	7,9	2,0	6,5	7,7	9,1	10,5	5,3	7,1	9,1	11,5	2,5	3,3	0,5	1,4	2,4	*1,0E-05*
	RPlmax	56,4	23,9	35,0	59,5	73,8	70,6	36,5	38,0	68,0	101,0	14,2	12,6	3,0	8,5	27,3	*0,01*
	RPrec	25,0	7,1	20,2	25,2	29,4	30,8	11,6	22,1	30,7	39,5	5,8	4,6	1,9	5,6	10,1	*5,0E-04*
	RPadet	96,8	2,4	95,5	97,5	98,2	96,9	2,4	95,4	97,5	98,8	0,1	0,0	-0,2	0,0	0,5	*n.s.*
	RPshen	2,5	0,3	2,3	2,6	2,8	2,9	0,4	2,6	2,8	3,1	0,3	0,1	0,3	0,3	0,3	*1,0E-05*
	dfα*1*	1,4	0,2	1,3	1,5	1,6	1,0	0,4	0,7	0,9	1,3	-0,4	0,1	-0,6	-0,5	-0,3	*1,0E-05*
	df α*2*	0,4	0,3	0,3	0,4	0,5	0,8	0,3	0,6	0,8	1,0	0,4	0,0	0,4	0,4	0,5	*1,0E-05*
	ApEn	0,6	0,1	0,5	0,6	0,6	0,8	0,1	0,7	0,8	0,8	0,2	0,0	0,2	0,2	0,2	*1,0E-05*
	Sampen	1,6	0,4	1,2	1,6	1,8	1,3	0,3	1,1	1,4	1,5	-0,2	-0,1	-0,1	-0,2	-0,3	*5,0E-04*
	D2	2,1	1,0	1,5	2,4	2,8	0,2	0,4	0,0	0,0	0,1	-2,0	-0,5	-1,5	-2,4	-2,8	*1,0E-05*

*All Spectral parameters calculated with the autoregressive model of stress, the HRV parameters shown in the table are those obtained from the shortest (30-second) time-segments. An example of reproducibility of quantitative assessment of HRVa, carried out from standard short-term and very short –term segments of the tachogram, is given in Fig. 4.

The correlation among HRV parameters, calculated from standard and very-short time-intervals has been previously evaluated (Fenici et al., 2013; Smith et al., 2013). However, the agreement between measurements obtained from the 300-, 120-, 60- and 30-second recordings was also confirmed in this study by the finding of intraclass correlation coefficients > 0.70 for the majority of calculated HRV parameters.

Although there were several inter-individual differences, in general a significant increase in heart rate compared with baseline rest conditions was confirmed as a primary indicator of stress-induced autonomic nervous system activation. In fact, under OS, the average heart rate ranged from 138-152bpm, with an average percentage increment of 43% above the officers' average daytime heart rates, most times in the absence of significant physical effort. The largest increase in heart rate was seen in one "*street stop of suspect drug dealers*" scenario ending in a shooting (Fig. 3), with individual peak HR of 192bpm (65% increment above the daytime average). This was closely followed by the "*call for domestic violence*" scenario (mean increment of 64.8%), "*building search*" scenario (63%) and "*high speed car chase*" scenario (61%).

Although sudden increments of HR even higher than 150% of the basal state were individually observed during simulated life-threatening confrontations, neither the absolute nor the percentage increment of HR could predict the tactical behavior of the POs during police tactical tasks. In fact, 50% of officers were tactically efficient even with very high HR, whereas the 50% who failed had HR within "ideal combat range" (i.e., below 145bpm, according to the Siddle's model; Grossman & Christensen, 2004; Siddle, 1995).

By applying DA against the whole dataset of HRV parameters a good separation was obtained between rest

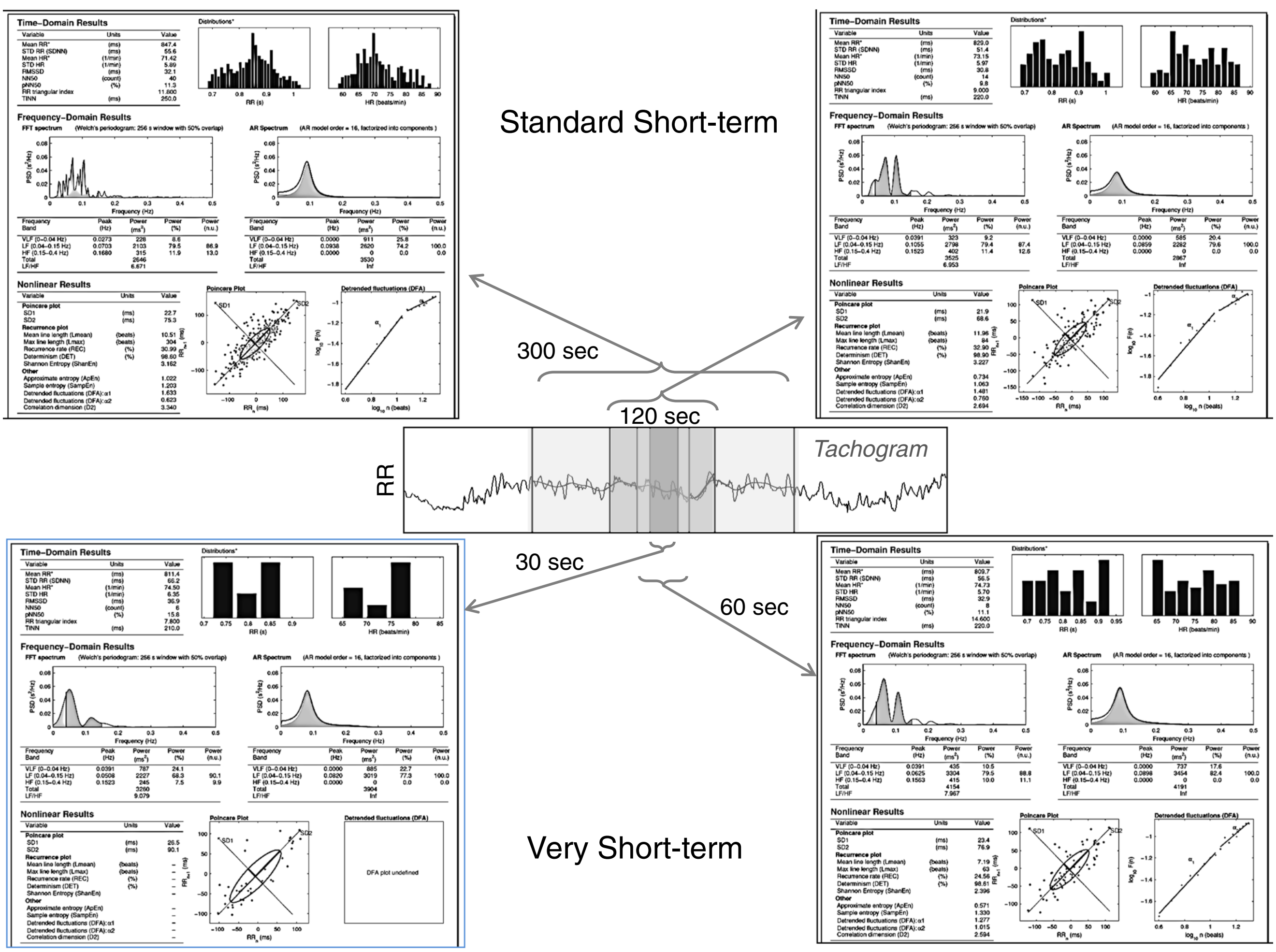

Fig. 4 Example of reproducibility of the quantitative assessment of HRV parameters carried out from standard short-term (300 and 120 sec) and very short –term (60 and 30 sec) segments, highlighted in different *gray* tones onto the tachogram (center). All selected intervals are centered within the median of the longest one (300 sec). It is immediately evident that the power spectra (middle of each window), the Poincarè plots and the DFA (lower graphics in each window) are similar

conditions and operational stress, occurring during the whole monitoring time (Fig. 5). Interestingly, the performance of the classifier is highly reproducible with data obtained from standard (120sec) and very short (60sec) time intervals. The performance of the classification rules based on single selected HRV parameters, and on the best combination of a subset of those parameters, is summarized in Table 5. For that subset of HRV parameters, the cutoff values were obtained to differentiate stress from rest conditions (for instance, referring to *D2*, if lower than 1.09).

The highest classification accuracy (92%) obtained was based on the combination of features *SD1*, *SD2*, and *dfα1*. The classification rule for that combination can be expressed as follows: The record is classified as stress if:

$$0.079 \times SD1 + 0.031 \times SD2 + 1.728 \times df\alpha 1 - 4.177 < 0 \qquad (1)$$

Similarly, it was found that in a subgroup of 70 subjects undergoing selective psychological (shoot/no shoot challenge at the simulator) or physical stress (effort with bicycle ergometer), the application of DA to HRV parameters was efficient to differentiate between the two kinds of stress, with a discrimination accuracy higher than 90% (Fig. 6).

Blood pressure measured at the end of each scenario was always significantly higher than before (average SBP 175 ± 18; DBP 110 ± 10; $p < 0.01$).

Discussion

Daily routine or extraordinary events, such as social interactions, emotions, physical and/or mental stress, and anxiety, require adaptations that are mediated by activation of the ANS. In most physiological conditions the two branches of the ANS have a reciprocal behavior, however the activation of the SNS represents a predominant response to situations implying psychological and physical coping for survival. Furthermore, there are conditions where a co-activation of both the SNS and PNS may occur (Paton et al., 2005) and, in tactical emergencies, other adaptive processes (i.e., secretion of hormones such as cortisol, catecholamine, prolactin, oxytocin and renin) contribute to maintain homeostasis as a part of the survival mechanism (McEwen, 2005; Van der Kar & Blair, 1999). Although emotions related to survival, such as anger and fear, have been widely investigated in the psychology laboratory (Kreibig, 2010; Kreibig et al., 2007; Stemmler et al., 2007), objective methods to quantify survival stress in real-world situations have not been reported so far.

If one aims at quantifying the dynamicity of ANS response to the acute stress induced by police operational situations, sophisticated recordings cannot be done and ECG is, at the moment, the only easily measurable parameter to rely on. However, since previous work has shown that absolute HR variation does not correlate with operational efficacy and success (Fenici et al. 1999a, 1999b; Fenici & Brisinda, 2002, 2004; Kemp & Diets 2008; Meyerhoff et al., 2004), HRVa has been recently applied to attempt a more efficient evaluation of tactical

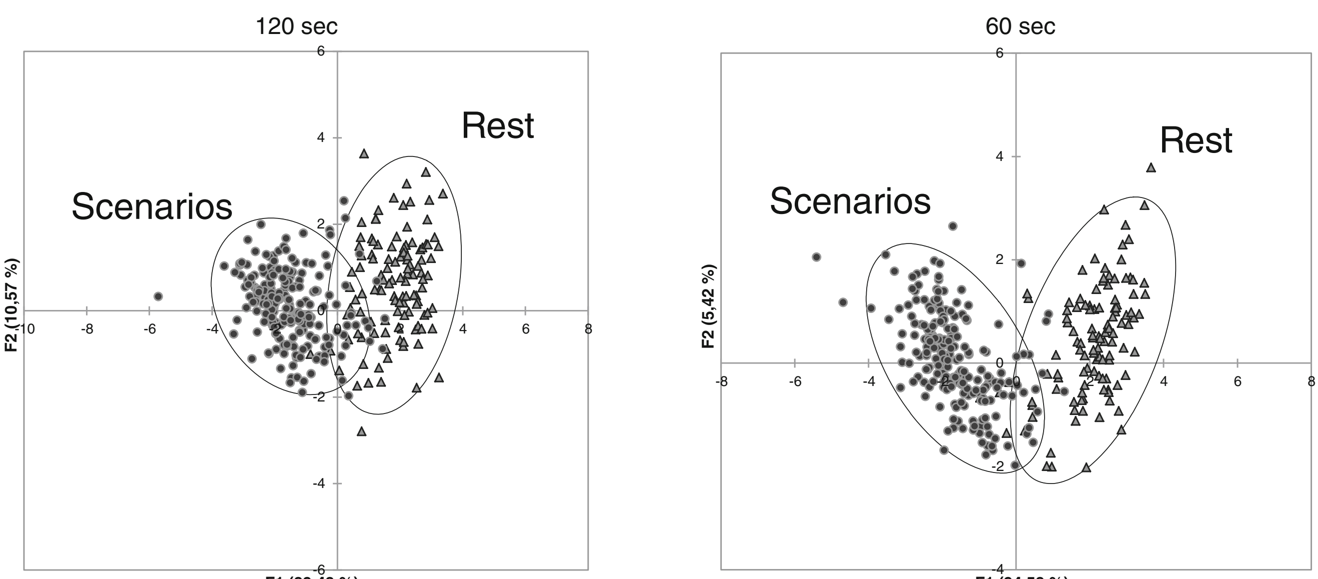

Fig. 5 Example of differentiation between rest (daily activity ▲) and operational stress (scenarios ●) obtained with discriminant analysis applied to the whole HRV data set of 107 police officers. The two situations are clearly separated independently from the duration of the selected interval (60 verso 120 seconds)

Table 5 Performance of the classification rules (Stress vs Rest conditions) based on single HRV parameter and combination of parameters

Parameters	Sens	Spec	PPV	NPV	ACC	*Classified as stress if*
SDNN	92%	85%	86%	91%	88%	*< 26,79*
RMSSD	86%	76%	78%	84%	81%	*< 20,71*
HF %	41%	61%	51%	51%	51%	*< 23,83*
HF ms^2	97%	60%	71%	96%	79%	*< 212,94*
SD1	86%	76%	78%	84%	81%	*< 14,74*
SD2	92%	85%	86%	91%	88%	*< 34,43*
dfα*1*	74%	82%	82%	74%	78%	*< 1,19*
ApEn	91%	88%	89%	89%	89%	*> 0,67*
SampEn	68%	65%	68%	65%	67%	*< 1,43*
D2	96%	83%	87%	95%	90%	*< 1,09*
SD1, SD2, dfα*1*	93%	91%	91%	93%	92%	*see formula #1*

stress (Fenici et al., 2011). Such an approach was based on scientific evidence that the sympathovagal balance, intended as synergistic organization finalized to adapt cardiac performance to situational requirements, can be assessed quantitatively, and that the effects of different emotions can be separated with HRVa (Kreibig, 2007; McCraty et al., 1995; Montano et al., 2009; Pagani & Lucini, 2008; Sloan et al., 1994; Stemmler et al., 2007).

However, previous studies have demonstrated that standard short-term HRVa (Task Force of The European Society of Cardiology and The North American Society of Pacing and Heart rate Variability Standards of Measurement et al. 1996) was not appropriate to evidence fast dynamic changes of ANS regulation occurring under the "fight-or- flight reflex" of police tactical tasks (Fenici & Brisinda, 2008a, 2008b; Nunan et al., 2008; Salahuddin et al., 2007; Smith et al., 2013). Therefore, in this study we have used time-varying HRVa to obtain real-time imaging of transient beat-to-beat variation of autonomic modulation in police officers, and to guide aimed quantitative HRVa from very short-term time-segments during normal daily activity and during acute stress operational stress induced by realistic tactical training.

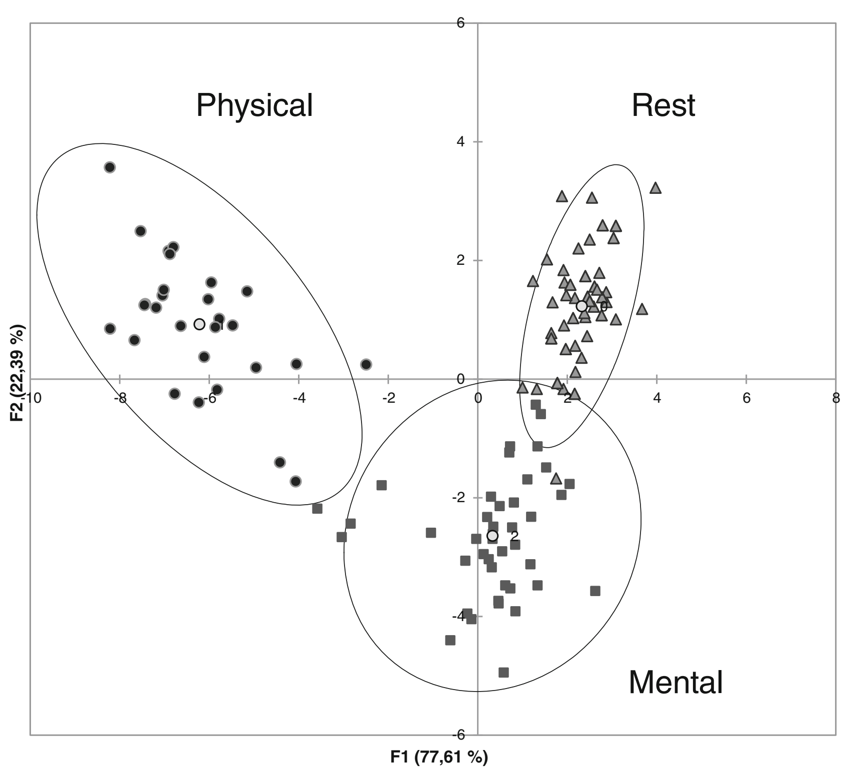

Fig. 6 Differentiation between selective mental stress (shooting simulator ■) and physical stress (●) at the bicycle ergometer obtained with discriminant analysis applied to a very short-term HRV data set of 70 police officers. The two kinds of stress are clearly separated also from rest (daily activity ▲)

With concern to spectral HRVa, although the average LF/HF ratio was reduced under operational stress, the difference was not statistically significant compared to normal daily activity (Table 4) when contrasted to a previous study (Fenici et al., 2011). This was probably due to a higher number of medium-stress scenarios in this study. In fact, in conditions of medium operational stress, such as during the "Tueller drill" (Fig. 3C left), a predominance of the LF component was observed, consistent with prevalent sympathetic activation (Montano et al., 2009). In contrast, in conditions of high stress, such as during high-risk scenarios ending in violent confrontation and shooting, a disappearance of the LF component was found, with marked decrease of the TP, and the residual spectral power sustained by HF components fluctuating in the frequency range between 0.2 and 0.5 Hz (Fig. 3C right). Such LF "shut off" with relative prevalence of the HF power was previously observed in similar cases implying sudden short-lasting life-threatening danger (Fenici et al., 2011), but it is still difficult to attempt a mechanistic interpretation, especially in light of the long lasting debate on the physiological meaning of the concept of sympathovagal balance (Eckberg, 1997; Montano et al., 2009; Thayer et al. 2012). In fact, none of the HRV spectral parameters can be considered univocally specific of cardiac response to ANS adaptation, because normalized LF power cannot uniquely estimate SNS outflow, being mediated also by PNS (Pomeranz et al., 1985; Reyes del Paso et al., 2013) and by baroreceptorial reflex (Akselrod et al., 1985; Zhong et al., 2006), whereas HF power variation may also reflect stress-induced changes in the respiratory rate. Moreover, similar atypical fluctuations of the FD spectral components were observed during high-intensity physical exercise and were considered consistent with mechanisms different from pure sympathetic-vagal interaction as the cause of HR increase (Buchheit et al., 2007; Casadei et al., 1995; Perini & Veicsteinas, 2003; Pichon et al., 2004).

Given the above uncertainties, and taking into account that operational stress response is a complex mixture of simultaneous emotional, neurophysiologic and endocrine adaptation (Ahmed et al., 1994; Terkelsen et al., 2005; Tulen et al. 1994), in this study quantitative analysis of HRV was also carried out with nonlinear methods to evaluate if the estimation of HRV complexity could improve the assessment of ANS modulation and provide a more robust method to differentiate different psychophysiological conditions. Interestingly, although some linear parameters were efficient discriminant indices between rest and stress (Table 5), the highest classification accuracy (92 %) was obtained based on the combination of features of nonlinear parameters (*SD1*, *SD2*, *and* $df\alpha 1$), all of them significantly reduced when compared with normal daily activity. Similarly, a significant reduction was observed for the correlation dimension (*D2*), another complexity index, which alone provided identification of stress with a discrimination accuracy of 90 %. This finding confirms that reduction in heart rate complexity during a high-stress condition may reflect lower adaptability and fitness of the cardiac pacemaker (Melillo et al., 2011; Schubert et al., 2009).

Moreover, since HRV is also a marker of the efficiency of the body's neural feedback mechanisms and reflects the individual's capacity to effectively organize physiological and behavioral resources in response to environmental demands (Thayer et al., 2012), individuals with low HRV might have reduced capacity to adjust rapidly and respond effectively to stressful stimuli. Conversely, quick adaptability and flexibility under stress determines individual capacity to respond efficiently and effectively to the challenges inherent in their work. Obviously, such evaluation is particularly relevant for police officers confronted in their work with diverse challenges, which require a wide range of fast behavioral responses. Thus, the study of HRV complexity during realistic scenarios might be an objective method to assess individual stress reaction and guide more tailored tactical training of police officers.

An important and, to the best of our knowledge, new finding of this study, is that with the application of discriminant analysis it is possible to obtain a clear-cut differentiation between psychological and physical stress, as demonstrated in a subgroup of officers who were exposed to selective mental (shoot/no shoot challenge at the shooting simulator) and physical (submaximal exercise test at the bicycle ergometer) stressors (Fig. 6). Such an observation, if confirmed in future studies, opens new possibilities to a more comprehensive understanding of the complexity of police operational stress.

Finally, psychological assessment demonstrated that the majority (93 %) of the investigated officers were free from symptoms related to anxiety and/or depression. This finding is consistent with the results of another recent study carried out with members of a police unit specialized in crowd and riot control, which demonstrated that the prevalence of mental health symptoms in Italian police officers was low (Garbarino et al., 2013). Nevertheless, subjective stress perceptions and feelings of fear and/or anger during the scenarios was rated as above 7/10 and was probably underestimated because about 15 % of the participants did not complete the subjective stress perception questionnaire after the scenarios.

Limitations

One limitation of this study is that respiratory activity was not simultaneously monitored during the ECG recording because our equipment does not provide that feature. Whether or not different breathing conditions may have an impact on the reproducibility and reliability of HRVa is still a debated question (Pinna et al., 2007; Pitzalis et al., 1996; Pitzalis et al., 1998; Toyry et al., 1995); however it has to be recognized that short-term HRV indexes associated with operational stress may be affected by changes in the respiratory pattern, not only in terms of frequency but also in terms of volume. Thus, controlling breathing rate might have given additional information for a more comprehensive interpretation of HRV changes associated with acute tactical stress, especially when the total power is almost null and the residual HRV is mostly related to HF components (Fig. 3C left), but at variable frequency (Grossman & Taylor, 2007).

Another limitation is that, in principle, spectral analysis of HRV requires stationary conditions (Montano et al., 2009) that are impossible under the arousal of tactical stress.

More selective quantification of the cardiac SNS and PNS regulation could be attempted by employing the "multisignal analysis of cardiorespiratory variability" (Chen & Mukkamala 2008), the "blind source separation" (Vetter et al., 2000) and the "principal dynamic mode of HRVa" (Zhong et al., 2006) methods. "Multisignal analysis" has the advantage that it is physiologically based, is not affected by random changes of breathing and is most effective with respect to the interaction between blood pressure and HR. On the other hand, the "principal dynamic mode analysis" has the practical advantage of requiring only a surface ECG measurement and therefore is foreseen as more feasible for tactical stress data evaluation.

Conclusions

Overall, this study has shown that time-varying HRVa is an efficient method to quickly evidence acute and transient changes of autonomic modulation of the heart rate in police officers undergoing realistic tactical training. Quantitative estimates of linear and nonlinear parameters evidenced significant differences useful to distinguish between normal daily activity and operational stress conditions. It was also confirmed by good intraclass correlation coefficients that the quantitative estimation of the majority of HRV parameters was not significantly affected by shortening the duration of the explored time-window from the standard 5 minutes (Task Force of The European Society of Cardiology and The North American Society of Pacing and Heart rate Variability Standards of Measurement et al. 1996) to very short (30-60 second) time-segments, which are more consistent with the time scale of police operational events. In addition, Discriminant Analysis of HRV parameters was capable of selectively differentiating not only between rest and stress conditions (Fig. 5), but also between mental and physical stress (Fig. 6). This last preliminary finding surely deserves further research to be confirmed on a wider number of cases and with more aimed protocols. However, based on present findings, it might be anticipated that advanced HRVa can be an efficient tool to investigate and improve the understanding of complex mechanisms underlying human response in force-on-force scenarios, which is necessary to design more efficient training methods for police officers to cope with operational stress.

However, we suggest that some caution is warranted in using this method. In fact, in order to guarantee quality and correctness of HRVa, preliminary editing of RR interval signals is still mandatory, especially when dealing with noisy data acquired during heavy and uncontrollable tactical dynamicity. Such editing, based on direct evaluation of appropriate ECG recordings, is at the moment impossible using sportive HR recorders, which have been validated only in quiet resting laboratory conditions (Nunan et al., 2008, 2009; Salahuddin et al. 2007). Furthermore, the development of specific equipment to monitor police officers is desired, consisting of a miniaturized digital ECG recorder, wirelessly connected to a wearable low-noise ECG electrode system. Further technological development foresees the inclusion of solid-state real-time HRV evaluation and data transmission capable of web-based remote monitoring (Salahuddin et al. 2007; Salahuddin & Kim, 2006). A more accurate evaluation of stress could be achieved with simultaneous recording of additional physiological parameters, such as blood pressure, posture, respiration rate, skin conductance and temperature. Reliable recording of such parameters under dynamic action is still only partial, even with the most recent technology (Nair et al., 2008).

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