Enhancing cardiac vagal activity: Factors of interest for sport psychology

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Abstract (150 words)

Self-regulation plays a critical role in sport performance. An objective, psychophysiological marker of self-regulation is cardiac vagal activity, the activity of the vagus nerve regulating cardiac functioning. The aim of this paper is to provide an overview of factors influencing cardiac vagal activity, which can be useful for athletes. Specifically, we organize this overview in two main domains: personal factors and environmental factors. Among the personal factors, we find the behavioural strategies that can be used by athletes: nutrition, non-ingestive oral habits, water immersion, body temperature reduction, sleeping habits, relaxation methods, cognitive techniques, praying, music, and exercise. Among environmental factors, we find those linked to the social (i.e., contact with humans and animals) and physical (i.e., aromas, lights, sounds, temperature, outdoor, altitude) environment. Future research directions are given, as well as practical implications for athletes and coaches.

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Keywords: heart rate variability, parasympathetic activity, cardiac vagal control, vagal tone, self-regulation, self-control, training, athletes, sport psychology

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Among the many psychophysiological parameters influencing sport performance, self-regulation appears to play a crucial role (Anderson et al., 2014). Self-regulation allows for flexible and appropriate adaptation of psychophysiological states in order to meet short-term and long-term goals, depending on the situational demands (Inzlicht, Schmeichel, & Macrae, 2014; Kotabe & Hofmann, 2015). An objective indicator of self-regulation is cardiac vagal activity (CVA), the activity of the vagus nerve regulating cardiac functioning, which can be inferred via heart rate variability (HRV; Laborde, Mosley, & Thayer, 2017; Thayer, Hansen, Saus-Rose, & Johnsen, 2009). In sport, a well-known way to influence CVA is the use of HRV biofeedback (Jimenez Morgan & Molina Mora, 2017). However many other factors can influence CVA. The aim of this paper is to offer an overview of factors influencing CVA, in order to help athletes understand better how to optimize their CVA, which should in turn contribute to optimize self-regulation processes linked to sport performance.

1.1. Cardiac vagal activity

CVA can be tracked through HRV (Chapleau & Sabharwal, 2011), referring to the variability in time between successive heartbeats (Malik, 1996). CVA is also sometimes referred to as cardiac vagal tone, cardiac vagal control, or parasympathetic activity, given the vagus nerve is the main nerve of the parasympathetic nervous system (Brodal, 2010). Nowadays the devices measuring HRV are small and light, and can be linked to smartphone apps for monitoring in in the field (Flatt & Esco, 2013). The indirect measurement of CVA through HRV, even if requiring careful considerations (Laborde & Mosley, 2016; Laborde, Mosley, et al., 2017), can be considered as efficient, non-invasive and cost-effective. Consequently, CVA can be seen as a particularly powerful tool to gain insights on how self-regulatory resources are mobilized and used by an athlete. In the following, we detail the role of CVA in self-regulation, as well as the aspects that need to be considered when aiming to increase self-regulation via CVA.

1.1.1. Cardiac vagal control and self-regulation

There are two main theoretical accounts regarding the connection between CVA and self-regulation: the polyvagal theory (Porges, 2007) and the neurovisceral integration model (Thayer et al., 2009). The polyvagal theory (Porges, 2007) focuses on how CVA facilitates prosocial behaviour through appropriate physiological and behavioural states. The neurovisceral integration model (Thayer et al., 2009) stems from the field of neurophysiology and links CVA to a large range of positive outcomes regarding executive functions, emotion, social and health regulation, as well as many other mechanisms related to the successful adaptation of the organism to the challenges individuals face on a daily basis (R. Smith, Thayer, Khalsa, & Lane, 2017; Thayer, Ahs, Fredrikson, Sollers, & Wager, 2012; Thayer et al., 2009). Both theories mainly focus on resting CVA, predicting that a higher resting CVA is linked to a better adaptive functioning, however resting CVA is not the only aspect that matters regarding self-regulation processes.

1.1.2. The 3 Rs of cardiac vagal control: Resting, Reactivity, and Recovery

To a certain extent, CVA is genetically inherited and therefore relatively stable (Neijts et al., 2014, 2015). Nevertheless, CVA is also sensitive to many factors that can result in positive and negative short- and long-term changes. To understand the role of CVA in self-regulation, it is important to consider three aspects, referred to as the 3 Rs of CVA (Laborde, Mosley, et al., 2017): Resting CVA, CVA Reactivity to events, and CVA Recovery from these events. All three aspects represent different levels of adaptability that are important for self-regulation processes underlying human behaviour.

Resting CVA refers to a baseline level, usually measured for a 5 min duration in a sitting or standing position (Malik, 1996). Reactivity represents the change between baseline and a specific event, like the exposure to a stressor. Physical stressors (e.g., Stanley, Peake, & Buchheit, 2013), mental stressors (e.g., Laborde, Brüll, Weber, & Anders, 2011; Laborde, Furley, & Schempp, 2015; Laborde, Lautenbach, & Allen, 2015), and health-related stressors (e.g., Thayer & Lane, 2007) contribute to a decrease in CVA. In terms of reactivity, both lower vagal withdrawal and higher vagal withdrawal can be facilitative, depending on the situation faced by the individual (Beauchaine, Gatzke-Kopp, & Mead, 2007). Consequently, the CVA level that allows an athlete to perform optimally is task and situation dependent. A smaller decrease in CVA, for example, was found to result in better cognitive executive performance under pressure (Laborde & Raab, 2013; Laborde, Raab, & Kinrade, 2014). When performing non-executive tasks, i.e. dart throwing under high pressure however, a larger cardiac vagal withdrawal appears to be beneficial (Mosley, Laborde, & Kavanagh, 2017). Finally, recovery refers to the process of restoration to a former or improved condition after having faced a stressor. Similar to reactivity, recovery is also crucial for successful adaptability of the organism (Stanley et al., 2013). Whilst this highlights the need to consider both CVA enhancing and CVA decreasing factors to facilitate the basis for an athlete's optimal performance, we focus this overview on CVA enhancing factors. Programs aimed at increasing CVA have already shown effective in improving self-regulation (e.g., Hansen, Johnsen, Sollers, Stenvik, & Thayer, 2004; Prinsloo et al., 2011). So far, however, no attempts have been made to summarize and to categorize the many factors that an individual can take care of in order to enhance CVA.

1.2. Rationale

The aim of this paper is to present an overview of factors that seem particularly suitable for influencing CVA in a sport context. Therewith, the paper has direct applied consequences, helping athletes and trainers becoming aware of ways to take action on factors influencing CVA, in order to improve their self-regulation abilities and consequently contributing to optimal performance states for training and competition, as well as to mental and physical health and general well being (Thayer et al., 2009). So far, to the best of our knowledge only one overview exist attempting to summarize the factors affecting HRV (Fatisson, Oswald, & Lalonde, 2016), however not specifically taking into account the HRV indicators reflecting CVA, therefore the link with self-regulation could not be established.

The large amount of papers published with HRV[1] makes it difficult to get the full picture of the factors influencing CVA, and therefore we intended here to break down the amount of evidence regarding enhancing CVA into meaningful categories for athletes and coaches.

1.3. Inclusion criteria

To be included in this overview, factors influencing CVA had to be practically applicable in a sport psychology context. Consequently, factors that are linked with CVA but cannot realistically be altered in athletes, such as age and gender (Antelmi et al., 2004) or personality (Mosley & Laborde, 2015), and factors that require the assistance of medical professional, like for example brain stimulations (Gulli et al., 2013), are not included in this overview. In terms of variables included, the methods described are based on studies analysing the following four HRV parameters expected to reflect CVA (Chapleau & Sabharwal, 2011; Grossman, van Beek, & Wientjes, 1990; Laborde, Mosley, et al., 2017; Malik, 1996): From the time-domain, the root mean square of the sum of the squared differences between adjacent normal RR intervals (RMSSD), the percentage of successive normal sinus RR intervals more than 50 ms (pNN50), and the peak-valley analysis, and from frequency-domain, high-frequency (HF), as well as respiratory sinus arrhythmia (RSA), referring to the variability in heart rate related to the respiratory cycle (Eckberg & Eckberg, 1982). Similar to HF, RSA is deemed to represent CVA (Berntson, Cacioppo, & Quigley, 1993) if the respiratory frequency is comprised between 9 and 24 cpm (Malik, 1996).

2. Overview of methods enhancing cardiac vagal activity in sport

Factors enhancing CVA are originating either in the person directly or in the environment. The following sections presenting the factors influencing CVA in sport psychology are organized according to this structure. The person dimension includes all factors linked to the behaviour of the person. Therefore, the behavioural strategies that an athlete could adopt in

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[1] A search on the Web of Science database on the 31st of March, 2018 with the keywords « heart rate variability », « vagal activity », « vagal tone », and « parasympathetic » returned 33,402 results

order to optimize CVA are listed here. The environment dimension includes factors of CVA linked to the social and physical aspects of the environment. Social factors are understood as interactions, or absence of interactions with other living beings, while physical factors refer to the physical properties of the environment. Unless specified, we always refer to the way factors influence resting CVA. Finally, we would like to stress that a systematic and exhaustive review of all factors within each category goes beyond the scope of this paper. Our aim is solely to illustrate the different factors influencing CVA, in order to provide insights regarding how they could be implemented in training or competition.

2.1. Person

There is a broad range of organised actions that an athlete can engage in to pursue their goals, which can be understood as behavioural strategies. In this section, factors influencing CVA that stem from behavioural strategies used by the individual are described, including nutrition, non-ingestive oral habits, water immersion, body temperature reduction, sleeping habits, relaxation methods, cognitive techniques, praying, music, and exercise.

2.1.1. Nutrition

The following three aspects of nutrition are of interest for an athlete: diet, beverages and supplementations.

2.1.1.1. Diet

Diet refers to the food a person consumes, the way the food is being consumed and to food-related life-style choices. Whilst food is being digested, CVA decreases (Lu, Zou, Orr, & Chen, 1999). There are however foods that despite the immediate reduction of CVA through digestion, lead to an enhancement of CVA on the long-term, such as pistachio nuts (Sauder, McCrea, Ulbrecht, Kris-Etherton, & West, 2014), soy oil (Holguin et al., 2005), yoghurt enriched with bioactive components (Jaatinen et al., 2014), green leafy vegetables (Park et al., 2009), and fatty fish (Hansen, Dahl, Bakke, Frøyland, & Thayer, 2010) like salmon (Hansen et al., 2014). A vegetarian life-style is associated with higher CVA (Fu, Yang, Lin, & Kuo, 2006). Other foods were shown to allow for a better recovery from stressful events, for example chocolate enriched with gamma-aminobutyric acid (Nakamura, Takishima, Kometani, & Yokogoshi, 2009). Fasting, which can be considered at first as a stressor, can lead to short-term reductions in CVA (Mazurak et al., 2013), while long-term effects of fasting seem to enhance CVA (Stein et al., 2012), possibly due to the resultant weight-loss (Sjoberg, Brinkworth, Wycherley, Noakes, & Saint, 2011). Conclusively, taking care of their diet is a simple way for athletes to enhance CVA. Athletes should consider the effects of different types of food on CVA, to help them make decisions about integrating them to their regular diet in order to optimize self-regulation processes.

2.1.1.2. Beverages

Certain beverages were found to influence positively CVA. The consumption of water (Routledge, Chowdhary, Coote, & Townend, 2002) and coffee (Richardson et al., 2004) can lead to CVA increases, as does moderate alcohol consumption (Quintana, Guastella, McGregor, Hickie, & Kemp, 2013). However, taking in large amounts of alcohol decreases CVA (Sagawa et al., 2011). In summary, athletes can easily increase their CVA levels by purposely choosing CVA-enhancing beverages, such as water, and incorporating those into their daily drinking habits.

2.1.1.3. Supplementations

There are a number of supplementations that have been shown to have a positive effect on CVA, including the herbs Ginseng, Oriental Bezoar and Glycyrrhiza (Zheng & Moritani, 2008), omega-three fatty acid (Sauder et al., 2013), DHA-rich fish oil supplementation (Sjoberg et al., 2010), vitamin B12 (Sucharita, Sowmya, Thomas, Kurpad, & Vaz, 2013), vitamin D (Hansen et al., 2014), magnesium (Almoznino-Sarafian et al., 2009), multi-vitamin-mineral preparation supplemented with guarana (Pomportes, Davranche, Brisswalter, Hays, & Brisswalter, 2015), and lavender capsules (Bradley, Brown, Chu, & Lea, 2009). Overall, supplements, which are easily addable to a diet without major changes, appear to be a reliable and simple way for an athlete to increase CVA.

2.1.1.4. Non-ingestive oral habits

Many common oral habits reduce CVA, such as tobacco smoking (Barutcu et al., 2005; Hayano et al., 1990; Sjoberg & Saint, 2011), inhaling second-hand tobacco smoke (Zhang, Fang, Mittleman, Christiani, & Cavallari, 2013), and waterpipe smoking (Cobb, Sahmarani, Eissenberg, & Shihadeh, 2012). Therefore it might be advisable for athletes to avoid the listed non-ingestive oral practices.

2.1.1.5. Water immersion

Water immersion includes the immersion of part or complete body in water. Both are associated with CVA increases, as it was shown for apnea in the form of scuba diving (Chouchou, Pichot, Garet, Barthelemy, & Roche, 2009) and for face immersion (Kinoshita, Nagata, Baba, Kohmoto, & Iwagaki, 2006). Importantly, CVA recovery from stressful events is improved through cold water immersion, rather than through warm water immersion (de Oliveira Ottone et al., 2014). For example, cold water (14°C) immersion was effectively implemented as a cooling technique after supramaximal exercise, resulting in greater CVA compared to passive rest in a hot environment (Buchheit, Peiffer, Abbiss, & Laursen, 2009). Thus, taking a cold bath after an intense training session can help athletes to restore CVA. In sum, water immersion can be an effective tool to increase CVA.

2.1.1.6. Body temperature reduction

As already stated in the section above, exposing the body to cold temperatures can enhance CVA. This can also be achieved with ice packs and fan cooling with intermittent water spray (Leicht et al., 2009a) or with cryostimulation (Hausswirth et al., 2013). During cooling treatment of exercise-induced hyperthermia, ice packs or fan cooling proved to be more effective than intravenous cold saline infusion to enhance CVA (Leicht et al., 2009b).

Therefore, cooling techniques can be used effectively to increase CVA, especially after being exposed to heat or after exercising.

2.1.1.7. Sleeping habits

Sleep, given its recovering and restoring qualities, is naturally important when it comes to enhancing resting CVA and improving CVA recovery after stressful events. CVA is positively related to subjective and objective sleep quality (Werner et al., 2015). Sleep deprivation on the other hand can cause decreases in CVA (Dettoni et al., 2012). Thus, assuring regular and sufficient, high-quality sleep when preparing for competitions is important to optimize CVA.

2.1.1.8. Relaxation methods

Relaxation methods refer to any intentional activity or method completed to attain a state of increased calmness and focus, making it a good candidate to increase CVA. Effective techniques to enhance CVA include acupuncture (Kitagawa, Kimura, & Yoshida, 2014), left nostril breathing (Pal, Agarwal, Karthik, Pal, & Nanda, 2014), massages (A. P. Smith & Boden, 2013), meditation with mindfulness training (Garland, Froeliger, & Howard, 2014), Qigong (a combination of posture and breathing exercises) (Chang, 2014), Reiki (a hands-on-healing technique) (Diaz-Rodriguez et al., 2011), slow paced breathing (Jimenez Morgan & Molina Mora, 2017; Laborde, Allen, Gohring, & Dosseville, 2017; Wells, Outhred, Heathers, Quintana, & Kemp, 2012) and yoga (Krishna et al., 2014). These methods may be particularly powerful tools for an athlete to face stressful situations and regulate effectively stress and emotions.

2.1.1.9. Cognitive techniques

In cognitive methods, the focus lies on the mind as an information processor. Purely cognitive methods found to increase CVA are behavioural therapy (in severely depressed patients (Carney et al., 2000) and cognitive reappraisal (whilst watching anger-inducing videos (Denson, Grisham, & Moulds, 2011). Together, existing evidence points towards a positive effect of cognitive methods on CVA, but cognitive methods are often combined with other methods, making it difficult at this stage to formulate specific suggestions for athletes.

2.1.1.10. Praying

With praying, people solemnly seeks and responds to God or another deity with their own or others struggles, regrets, needs or desires (Cole, 2010). Praying is linked to higher CVA (Doufesh, Ibrahim, Ismail, & Wan Ahmad, 2014), as is spirituality (Berntson, Norman, Hawkley, & Cacioppo, 2008). In sum, praying and religious beliefs in general can have positive effects on CVA.

2.1.1.11. Music

Music is known to have “calming” or “stimulating” properties for athletes (Karageorghis & Priest, 2012a, 2012b) that are also reflected in CVA increases or decreases associated with music. Listening to sedative music, for example, is linked with higher CVA than listening to excitative music (Iwanaga, Kobayashi, & Kawasaki, 2005). Physically producing music, e.g. by singing can also increase CVA (Grape, Sandgren, Hansson, Ericson, & Theorell, 2003). Given its accessibility for athletes, music seems to be a reliable and simple way to influence CVA. Before a competition, an athlete would then choose deliberately to use a calming music to enhance CVA if the purpose.is to manage stress and/or to enter the competition in a relaxed state, while stimulating music could be used deliberately to decrease CVA and provoke a higher state of alertness.

2.1.1.12. Exercise

Exercise, defined as physical activity that is performed in a structured, planned and repetitive manner, is generally regarded as a straightforward way to achieve long-term increases in CVA (Hautala, Kiviniemi, & Tulppo, 2009). It is important though to take a closer look at the short-term effects of exercising on CVA levels. During the exercise, the body needs to be activated to ensure energy mobilization, and thus, CVA decreases. After the exercise has stopped, the body starts to recover and CVA rises again, the speed of the recovery constituting an index of fitness level (Stanley et al., 2013). Exercise is presumably already a predominant part of an athlete's everyday life, which gives them the benefit of higher CVA as compared to non-active individuals (Rossi, Ricci-Vitor, Sabino, Vanderlei, & Freitas, 2014). For non-active individuals, starting to engage in regular, moderate exercise seems a promising way to provoke long-term increases in CVA (Hautala et al., 2009).

In summary, the listed behavioural strategies present voluntary actions that can be applied by athletes in everyday life, in training or in competition, and can help regulating optimally one's behavior when facing pressure (Thayer et al., 2009).

2.2. Environment

In the following section, factors that stem directly from the social and physical aspects of the environment are described.

2.2.1. Social environment

The social environment of an individual can be understood as the sum of regular interactions with other humans or animals, or the lack of them.

2.2.1.1. Contact with humans

From an early age on, social interactions seem to have an important influence on CVA. As such, children with coercive-preoccupied patterns of attachment display lower CVA (Kozlowska et al., 2015). Throughout life, levels of social integration seem to be directly and positively associated with CVA (Gouin, Zhou, & Fitzpatrick, 2015). Humans, as social creatures, react to regular social contact with other human beings and to social support of others or simply the subjective feeling of it, with higher CVA (Maunder et al., 2012). Further, the physical touch of another human being (Feldman, Singer, & Zagoory, 2010), love (Schneiderman, Zilberstein-Kra, Leckman, & Feldman, 2011) and sexuality (Costa & Brody, 2012) are associated with higher CVA.

It can therefore be advisable to increase the level of social contact outside or during training by engaging in partner exercises, and to always ensure that a feeling of social support is granted in order to enhance CVA. Taken together, findings suggest that facilitating social contact and engaging in its physical manifestations is a promising way to increase CVA.

2.2.1.2. Contact with animals

The positive effect of social contact on CVA is not limited to contact with human beings but can also be found for contact with animals. Owning a pet is generally linked with higher CVA (Aiba et al., 2012). Taking a dog for a walk or patting a dog is associated with CVA increases (Motooka, Koike, Yokoyama, & Kennedy, 2006). In sum, social contact with humans and animals seems to have a positive influence on CVA, supporting the link with CVA and social functioning proposed by the polyvagal theory (Porges, 2007).

2.2.2. Physical environment

In the next section, physical factors of the environment that influence CVA are described, including aromas, lights, temperature, sound, the outdoor environment, and altitude.

2.2.2.1. Aromas

There are multiple aromas that are linked with CVA increases, including cedrol, which is mostly found in essential pine tree oils (Dayawansa et al., 2003), and yasmin tea (Inoue, Kuroda, Sugimoto, Kakuda, & Fushiki, 2003). Certain aromatherapies, such as Lavender aromatherapy, were also positively linked CVA (Duan et al., 2007; Matsumoto, Asakura, & Hayashi, 2013). It is still unclear, if displeasing or foul aromas have negative effects on CVA. Positive aromas, however, may present a simple, accessible tool for athletes to increase CVA.

2.2.2.2. Lights

Certain light conditions are associated with high CVA, such as bright light in patients with severe depression (Rechlin, Weis, Schneider, Zimmermann, & Kaschka, 1995), and oscillating coloured light, as compared to white light (Grote et al., 2013; Schafer & Kratky, 2006). Darkness, commonly a signal for the organism that it is time to rest, is also associated with high CVA (Boudreau, Yeh, Dumont, & Boivin, 2012). Taken together, light exposure seems to be a reliable and simple way to influence CVA, which makes it an appealing strategy to use for athletes given its place in our everyday lives.

2.2.2.3. Sounds (excluding music)

Sound is here understood as any inevitable audio signal from the environment. It is different from the category of music, as listening to music or playing music, is something a person chooses to engage in at times, whereas the sounds of the environment are constantly present. Generally, unpleasant sounds lead to reductions in CVA, such as sounds of violence and the crying of a baby (Tkaczyszyn et al., 2013). Also, higher levels of noise exposure in an individual's daily life are associated with decreased CVA (Kraus et al., 2013). On the other hand, natural sounds were linked to higher CVA in a virtual natural environment, as compared to no sound and a control group (Annerstedt et al., 2013). Thus, an athlete could aim to keep unpleasant noise exposure to a minimum, in order to avoid CVA reductions and consider playing pre-recorded natural sounds to increase CVA. Overall, shaping ones daily auditory environment presents a simple way of enhancing or decreasing CVA.

2.2.2.4. Temperature

Temperature, here, refers to the degree of heat of the individual's environment. As already stated in the person section, temperature can influence CVA. Following ambient cold exposure, CVA seem to increase after acclimation (Makinen et al., 2008). Higher ambient heat exposure decreases CVA (Bruce-Low, Cotterrell, & Jones, 2006; Sollers, Sanford, Nabors-Oberg, Anderson, & Thayer, 2002). Avoiding high ambient temperatures during the warm season is associated with higher CVA in elderly people (Ren et al., 2011). When exercising in hot environments, heat tolerance indexed with CVA can be improved through frequent exposure, but the effects disappear after frequent heat exposure stops (Flouris et al., 2014). Finally, abrupt changes in temperature lead to a CVA withdrawal, before the organism adapts (Peng et al., 2015). To sum up, CVA appears to be increased by cold environments, whereas hot environments tend to decrease CVA. Prior acclimation to the climate of the competition before the competition seem in any case important in order to decrease the strain of temperature change on CVA.

2.2.2.5. Outdoor environment

Outdoor environments can roughly be categorized as urban environment (i.e., city) and as natural environments (i.e., forest). Going for a walk in a forest (Lee et al., 2014) or in a park (Song et al., 2014) is associated with higher CVA. It seems crucial to be physically present in the natural environment though, as exposure to a virtual natural environment had no effect on CVA (Annerstedt et al., 2013). On the contrary, CVA reductions are found in association with air pollution outside (Pope et al., 2004), ambient ozone (Jia et al., 2011) and chronic exposure to organic solvents (Murata et al., 1994). Athletes striving to maximise CVA could therefore train more outside in a natural environment rather than indoors. They should, however, pay attention to factors like air pollution and ozone. In conclusion, visiting natural environments is a simple way of enhancing CVA, in line with the common assumption that natural environments possess stress-reducing qualities (Ulrich et al., 1991).

2.2.2.6. Altitude

Altitude has the potential to trigger changes in CVA. For example, when an individual reaches an altitude of 2700 meters, measured from sea level, compared to 170 meters (Trimmel, 2011), and or 3440 meters (Huang et al., 2010), this is associated with significant decreases in CVA. However, when the organism adapts to the high altitudes, CVA progressively increases and can therefore be used as a marker of adaptation to high altitude hypoxia (Bhaumik, Dass, Bhattacharyya, Sharma, & Singh, 2013; Passino et al., 1996). When individuals return to lower altitude levels after dwelling in moderate altitudes, a positive effect on CVA remains for a certain time (Schobersberger, Leichtfried, Mueck-Weymann, & Humpeler, 2010), which mirrors the cardiovascular adaptations of altitude on training (Hamlin, Lizamore, & Hopkins, 2018; Lizamore & Hamlin, 2017). The effects of training may differ according to the altitude: for example the same training loads have been found to induce a positive effect on CVA and performance at 1200 m but not at 1850 m (Schmitt et al., 2006). This indicates that future research should clarify the exact duration and altitude for maximizing CVA enhancing effects. Summing up, the evidence points towards the benefits of spending time at higher altitudes, given after an initial decrease in CVA the organism adapts and CVA can reach its initial level or even a higher level than before, and these CVA changes are preserved during a certain time, even after returning to sea level.

In conclusion, there is a broad range of factors pertaining to the physical environment that athletes can take care of in order to optimize CVA.

3. Future directions

This paper constitutes the first overview of factors influencing CVA that are readily applicable in the sport domain. This endeavour seemed crucial, given the importance of CVA with regards to self-regulation (Porges, 2007; Thayer et al., 2009). Stressors typically lead to a decrease in CVA, which hinders the effectiveness of self-regulation processes (Thayer et al., 2009). Athletes, however, have to face stressors on a daily basis, whilst maintaining a high level of performance and managing the pursuit of long-term goals, which constantly requires self-regulation. Enhancing CVA is therefore a highly promising way of improving athletes self-regulation when facing stressors, ultimately resulting in better cognitive, emotional, social, and (physiological) health regulation (Porges, 2007; Thayer et al., 2009) as well as in superior athletic performance (Anderson et al. 2014; Dupee, Werthner, & Forneris, 2015; Ravizza, 2006). Athletes can now make informed decisions regarding applying specific behavioural strategies or implementing some of the suggested changes to the surrounding environment in their daily routines to further optimize CVA. Together, this can lead to crucial improvements in self-regulation and in sport performance.

With the overview at hand, we hope to inspire researchers and practitioners alike to consider CVA as a useful marker for self-regulation, which is worth to be investigated and monitored in order to optimize performance. Future research should aim to investigate dose-response relationships, quantify effects regarding magnitude and duration, and identify improvement and impairment thresholds, in order to identify the situations where too much CVA is not anymore helpful for self-regulation (Kogan, Gruber, Shallcross, Ford, & Mauss, 2013). Finally, there is also the need to explore the relationships of CVA with the different aspects of athletic performance where self-regulation is involved and to identify the potential moderators interacting with the effects of the factors influencing CVA.

4. Potential limitations

The aim of this paper was not to be exhaustive regarding the factors influencing CVA, but to provide the reader with an overview of influential factors that could potentially be useful for athletes. The studies cited serve as illustrations of the categories, and they are not methodologically evaluated. Further, we also do not quantify the effects we report through effect sizes. Systematic reviews and meta-analysis on the factors reported would have been beyond the scope of this paper, and constitute directions for future research.

Some cautions need to be taken when making inferences regarding CVA enhancements. We need to point out that in this paper, we almost exclusively consider higher CVA as being the desired output, given its positive associations with self-regulation at the cognitive, emotional, and health levels (Thayer et al., 2009). It has, however, recently been proposed that the more-is-better concept is not always applicable for CVA. Instead, the association between CVA increases and positive outcomes for the individual may be nonlinear, for example with respect to subjective well being (Kogan et al., 2013) and risk of mortality (Stein, Domitrovich, Hui, Rautaharju, & Gottdiener, 2005). As a consequence, researchers should aim to identify cut-off levels for when increasing CVA stops being beneficial for an athlete’s performance. Additionally, there are situations in training and in competitions where a high-level of activation is required, which is reflected in a lowered CVA. Lastly, we would like to call the attention of researchers and athletes aiming to measure

CVA to the fact that measures of HRV are no direct measures of CVA but only indirectly represent CVA. Therefore, observed changes in HRV may result from factors other than CVA, such as modification of the baroreflex sensitivity (Desai, Watanabe, Laddu, & Hauptman, 2011). If basic methodological considerations are considered though (Laborde, Mosley, et al., 2017; Quintana & Heathers, 2014), CVA, inferred from HRV, presents a conclusive and objective indicator of self-regulation.

5. Concluding Remarks

With this paper, we propose the first structured overview of the quickly increasing body of research related to the factors influencing CVA that can be applied in a sport context and potentially result in superior athletic performance, improved general health and improved well-being through better self-regulation. Through this endeavour, we hope to inspire researchers and practitioners alike. Many of the factors can be incorporated into daily routines or training routines of athletes in order to increase CVA, or they can be applied in particularly stressful situations in order to aid CVA recovery.

We hope to inspire researchers to answer open questions regarding dose-response relationships, thresholds, and moderators, in order to better understand how to optimize CVA. Moreover, this overview forms the groundwork for further systematic review and meta-analysis. We encourage researchers to expand upon it, to evaluate the quality of studies and to compare effect sizes, which are extremely critical steps to being able judge the importance of the factors identified in this overview and forming precise recommendations. Finally, potential confounding factors that should be taken into consideration and possibly be controlled for when studying CVA in a sport context can be derived from this overview. The use of CVA in the sport context is still in its infancy, and there is still much to learn about how the vagus nerve can inform sport performance.

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