

**In the Maze of Self-Control and Self-Regulation: Taking into  
Account Self-Ratings, Executive Functions, Heart Rate  
Variability, and Action-State Orientation**

Von der Pädagogischen Hochschule Schwäbisch Gmünd  
zur Erlangung des Grades eines

Doktors der Philosophie (Dr. phil.)

angenommene Dissertation von

Daniel Groß

aus

Ludwigsburg

Schwäbisch Gmünd, 2020

Erstgutachter: Prof. Dr. Carl-Walter Kohlmann

Zweitgutachter: Prof. Dr. Andreas Schwerdtfeger

Fach: Pädagogische Psychologie und Gesundheitspsychologie

Abgabetermin der Dissertation: 30.09.2020

Similarly, encourage the young men to be self-controlled.

*Titus 2:6 New International Version (NIV)*

Like a city whose walls are broken through is a person who lacks self-control.

*Proverbs 25:28 NIV*

But the fruit of the Spirit is love, joy, peace, forbearance, kindness, goodness, faithfulness, gentleness and self-control. Against such things there is no law.

*Galater 5:22–23 NIV*

# Content

LIST OF TABLES .....	iii
LIST OF FIGURES .....	v
LIST OF ABBREVIATIONS .....	vi
ACKNOWLEDGEMENTS .....	vii
ABSTRACT .....	ix
References.....	xiv
GENERAL INTRODUCTION .....	1
1. Beginnings of self-control measurement and the importance of childhood self-control for future outcomes.....	2
2. Constructs, variables, and ratings to measure self-control and self-regulation.....	4
2.1. Trait self-control and impulsivity .....	6
2.2. State self-control .....	9
2.3. Executive functions.....	11
2.4. Heart rate variability .....	15
2.5. Association between different self-control variables and ratings, and their predictive power.....	17
3. Theories and moderators of self-control and self-regulation .....	20
3.1. Depletion of state self-control.....	20
3.2. Action-state orientation.....	23
3.3. Combination of variables to determine self-control .....	26
4. Training of self-control and self-regulation .....	28
4.1. Executive functions (including working memory capacity) .....	29
4.2. Heart rate variability .....	31
4.3. Action-state orientation.....	33
5. Overview of the studies.....	36
5.1. Study 1: Executive functions and heart rate variability .....	36
5.2. Study 2: Self-control capacity.....	37
5.3. Study 3: Interventions to increase heart rate variability .....	38
6. References general introduction.....	39
STUDY 1.....	81
STUDY 2.....	82
STUDY 3.....	83
Abstract.....	84
1. Introduction .....	85

1.1.	Resonance frequency training.....	85
1.2.	Progressive muscle relaxation.....	87
1.3.	Present study .....	88
2.1.	Participants.....	89
2.2.	Ethical consideration.....	89
2.3.	Heart rate variability measurement.....	89
2.4.	Intervention groups and active control group .....	90
2.5.	Data analyzing and processing.....	91
4.	Discussion .....	96
4.1.	Limitations and some further proposals for subsequent studies .....	97
5.	References .....	99
	GENERAL DISCUSSION.....	106
1.	Summary of the studies .....	106
1.1.	Study 1: Executive functions and heart rate variability .....	106
1.2.	Study 2: Self-control capacity.....	108
1.3.	Study 3: Interventions to increase heart rate variability .....	110
2.	Final statement .....	112
3.	References general discussion.....	115

LIST OF TABLES

**LIST OF TABLES**

**GENERAL INTRODUCTION**

Table 1. *Example Items of the Three Relatively Frequently Used Self-Control Scales.* ..... 7  
Table 2. *Basic Executive Functions (EFs) and their Measure.* ..... 14

**STUDY 3**

Table 1. *Linear Mixed-Effect Model, using Resting HRV (ln RMSSD) as the Criterion.* ..... 94

LIST OF BOXES

**LIST OF BOXES**

**GENERAL INTRODUCTION**

Box 1. Five Factors of Impulsivity (Stahl et al., 2014)..... 9  
Box 2. Item Examples of the Three Action Control Subscales (Kuhl, 1994b)..... 24

LIST OF FIGURES

**LIST OF FIGURES**

**ABSTRACT**

*Figure 1.* Graphical overview of Study 1; only the interactions are shown. .... x  
*Figure 2.* Graphical overview of Study 2; only the interactions are shown..... xi  
*Figure 3.* Graphical overview of Study 3..... xii  
*Figure 4.* Graphical overview of the expected associations for all three studies; only the interactions are shown. .... xiii

**GENERAL INTRODUCTION**

*Figure 1.* Example of a Simon task, a Stroop task, or a Flanker task. .... 10

**STUDY 3**

*Figure 1.* Time-varying effects of each group (dual-task; PMR = progressive muscle relaxation; RFT = average resonance frequency training); HRV = heart rate variability; Day = daily HRV measurement; grey shades correspond to the 95% confidence interval, respectively..... 93  
*Figure 2.* Daily HRV measurement of each participant; the graph also includes the individual linear equation (random effects) of each participant..... 95

**GENERAL DISCUSSION**

*Figure 1.* Graphical overview of Study 1; only the interactions are shown; significant interactions are shown with solid lines; the significant interactions became significant mainly because of the state-oriented individuals since the Johnson Neyman tests were not significant for action-oriented individuals. .... 108  
*Figure 2.* Graphical overview of Study 2; only the interactions are shown; significant interactions are shown with solid lines. .... 110  
*Figure 3.* Graphical overview of Study 3; the intervention group with a significant effect is shown with a solid line..... 112  
*Figure 4.* Graphical overview of all three studies; only the interactions are shown; significant interactions are shown with solid lines..... 113

## LIST OF ABBREVIATIONS

### LIST OF ABBREVIATIONS

ANS	Autonomic Nervous System
AOD	Demand-Related Action-Oriented
AOD-SOD	Demand-Related Action-State Orientation
AOF	Failure-Related Action-Oriented
AOF-SOF	Failure-Related Action-State Orientation
AOP-SOP	Performance-Related Action-State Orientation
AOP	Performance-Related Action-Oriented
ASC-90	Action Control Scale
BIS-15	Barratt Impulsiveness Scale – short version
BRIEF	Behavior Rating Inventory of Executive Function
CAN	Central Autonomic Network
EFs	Executive Functions
HR	Heart Rate
HRV	Heart Rate Variability
Hz	Hertz
PMR	Progressive Muscle Relaxation
RFT	Resonant Frequency Training
RMSSD	Root Mean Square of Successive Differences
RR/NN interval	Time interval between two subsequent R- peaks/ normal-to-normal intervals
RSA	Respiratory Sinus Arrhythmia
SSCCS	State Self-Control Capacity Scale
SOD	Demand-Related State-Oriented
SOF	Failure-Related State-Oriented
SOP	Performance-Related State-Oriented
TOTE model	Test-Operate-Test-Exit model
WMC	Working Memory Capacity

## ACKNOWLEDGEMENTS

### ACKNOWLEDGEMENTS

Thanks, Prof. Dr. Carl-Walter Kohlmann, for being my waymaker, guide, motivator, supporter, critical questioner, perspective provider, for being so open-minded, and for believing in me as a whole person, and my research. That is who you were to me throughout this journey—my supervisor. You were truly the wind in my back that held me on the track.

Thanks, Prof. Dr. Andreas Schwerdtfeger, for reading and reviewing this thesis and for agreeing to be my second supervisor. I appreciate that.

Thank you, Hanna, for being a true friend and not just an office mate. Thank you very much for your open ear and your advice, our conversations were always really helpful.

Thanks, Mom and Dad, for believing in me and my journey so far. For planting a seed in my heart that is now rising and continues to develop. Thank you for your unconditional love and the opportunity to study which helped me discover my passion for psychological research.

Thanks, Manu, Judit, Noah, Ben, Ella, and Mila, for your BMW to drive to Schwäbisch Gmünd and everywhere I want to drive. And thank you for all the fun we had whenever I was at your house in Hessigheim.

Thanks, Frieder, for all the football games that we watched online. It helped me to find rest on this journey.

Thanks, Bine, and Tilo for supporting me and for your constant encouragement and love.

Thanks, Bekky, and Michele, for proofreading large parts of this work. Your work was the icing on the cake.

## ACKNOWLEDGEMENTS

Last but not least, many thanks to Talitha, for your love, your encouragement, and your constant belief in me and my work, and to Jesus, for always being with me every day of my life and especially on this journey.

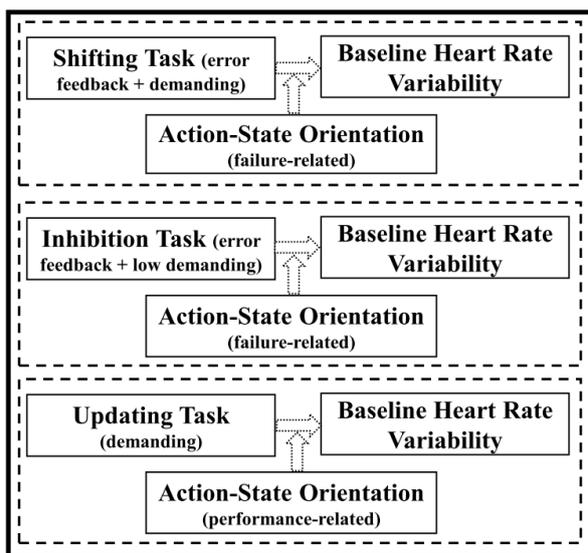
## ABSTRACT

### ABSTRACT

This dissertation firstly focuses in Study 1 (see Figure 1) on the low relationship between the measurement of cognitive functions that support successful self-regulation, called executive functions (EFs), and vagally mediated resting heart rate variability (HRV), the change in the time intervals between two consecutive heartbeats (called RR/NN intervals or interbeat intervals), which results from the parasympathetic activity of the autonomic nervous system, in particular of the vagus nerve. Vagally mediated HRV should be associated with EFs due to the neurovisceral integration model (Thayer et al., 2009; Thayer & Lane 2000, 2009) which indicates that the prefrontal cortex is an important cortex region for both vagally mediated HRV and EFs but is questioned by two *meta-analyses* (Holzman & Bridgett, 2017; Zahn et al., 2016). In this thesis, it is expected that this relationship is low because past studies often did not consider individual implicit affect and attention regulation capacity which can be measured by action-state orientation (cf. Fischer et al., 2015; Koole & Jostmann, 2004; Kuhl, 1994a, 1994b; Wolff et al., 2016). In general, in demanding situations, action-oriented individuals can more easily up-regulate positive affect and self-generate rewarding incentives (demand-related action-state orientation subscale; Kuhl, 1994a, 1994b), down-regulate negative affect (failure-related action-state orientation subscale; Kuhl, 1994a, 1994b), stay focused on a task until it is finished (performance-related action-state orientation subscale; Kuhl, 1994a, 1994b), and thus mobilize their EFs more efficiently. State-oriented individuals, however, have problems with motivating themselves, staying focused on the task until it is finished, regulating the positive and negative affect, and thus with effectively mobilizing EFs (e.g., Gröpel et al., 2014; Jostmann & Koole, 2006, 2007; Koole et al., 2012; Kuhl, 2000; Wolff et al., 2016). Study 1 identified that the relationship between EF task performance (in a shifting task, an inhibition task, and an updating task) and vagally mediated resting HRV was moderated by failure-related (shifting and inhibition task) or performance-related (updating task) action-state orientation subscales (Kuhl, 1994a, 1994b) if demands and error feedback of the EF tasks were also being

## ABSTRACT

considered. However, the Johnson-Neyman tests only indicated a significant relationship for state-oriented individuals<sup>1</sup>, which also differed in the direction between demanding (shifting and updating task) and low-demanding (inhibition task) EF tasks, indicating that in low-demanding EF tasks state-oriented individuals can even outperform action-oriented individuals (cf. Koole et al., 2012; Koole et al., 2005). Because of the non-significant relationship for action-oriented individuals, Study 1 cannot fully confirm the neurovisceral integration model (Thayer et al., 2009; Thayer & Lane 2000, 2009).



*Figure 1.* Graphical overview of Study 1; only the interactions are shown.

In Study 2 (see Figure 2) possible indicators for state self-control capacity (measured by a Simon task) after demanding EF tasks, as well as for trait self-control (measured by a questionnaire) were analyzed by focusing on the interplay between control capacity and self-motivation (indicated by the demand-related action-state orientation subscale; Kuhl, 1994a, 1994b). As possible control capacity variables, Study 2 focused on working memory capacity (WMC), based on the integrative theory of self-control (Kotabe & Hofmann, 2015), and on

---

<sup>1</sup> This may be because demanding EF tasks were so stressful, that they exceeded even the profound affect and attention regulation capacity of action-oriented individuals (cf. Koole et al., 2005) or on the fact that being action-oriented is significantly associated with socially desirable responding (Diefendorff et al., 2000).

## ABSTRACT

cardiac vagal control (index by vagally mediated resting HRV), a possible physiological index of control capacity (not a resource itself), based on the vagal tank theory (Laborde et al., 2018b). Since the vagal tank theory (Laborde et al., 2018b) also focuses on within-subject changes in cardiac vagal control as a possible index of state self-control capacity, baseline to post-event cardiac vagal control changes were also analyzed. Following the integrative theory of self-control (Kotabe & Hofmann, 2015), the results indicated that state, as well as trait self-control, is predicted by an interplay of WMC, and demand-related action-state orientation. Focusing on the vagal tank theory (Laborde et al., 2018b), the results indicated that state self-control capacity can best be detected by the within-subject changes in cardiac vagal control (state-oriented individuals with a low WMC [as expected by the integrative theory of self-control; Kotabe & Hofmann, 2015] indicated the greatest reduction in cardiac vagal control after the demanding EF tasks). However, between-subject differences of cardiac vagal control seem to be ambiguous and less clear for predicting self-control capacity since they are only weakly related to trait self-control if cardiac vagal control is considered without action-state orientation (i.e., only the correlation is considered). These differences here between state and trait self-control might be because the variable and stable components of HRV are of different sizes (Bertsch et al., 2012).

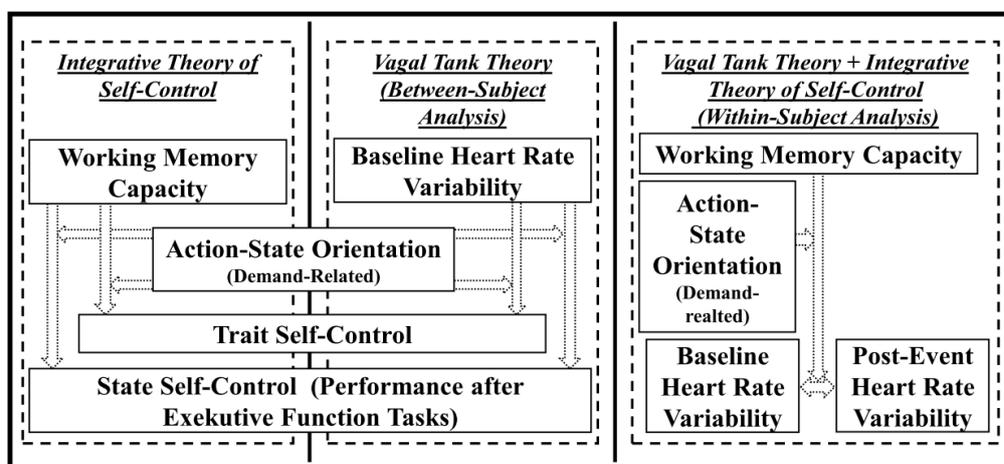
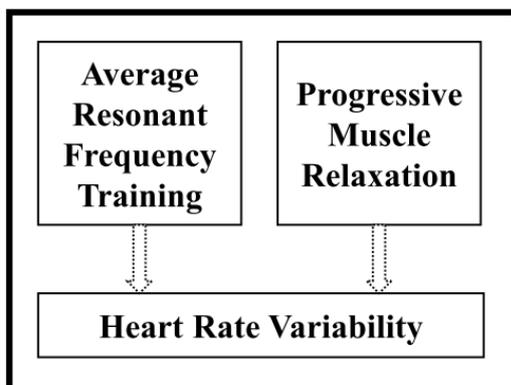


Figure 2. Graphical overview of Study 2; only the interactions are shown.

## ABSTRACT

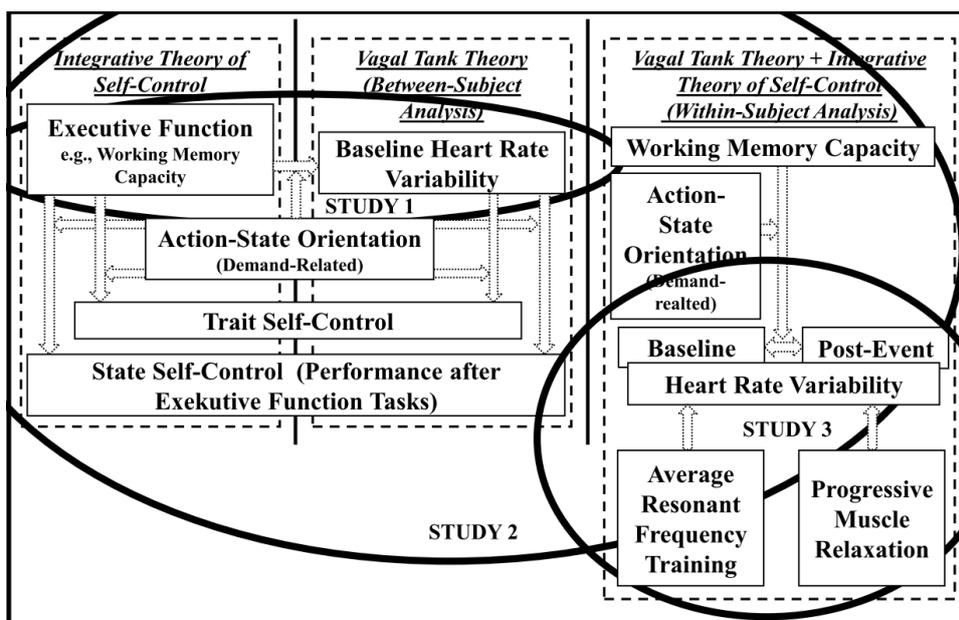
Since higher vagally mediated HRV is often associated with health, better self-regulation and self-control capacity, increased EFs, adaptability (more flexibility to reaction on different situations), and resilience (e.g., Segerstrom & Nes, 2007; Shaffer & Grinsberg, 2017; Thayer et al., 2009, 2012), Study 3 (see Figure 3) examined whether it is possible to increase vagally mediated HRV in healthy subjects with average resonant frequency training (RFT; i.e., 6 breaths/minute) and progressive muscle relaxation (PMR) within 77 days. The effects were tested against an active control group, which did a dual-task consisting of a balance task with parallel cognitive tasks. Every morning, participants measured resting vagally mediated HRV with a mobile device by themselves. A linear mixed-effect model, using random slopes (daily HRV measurement), and random intercepts (participants) indicated that only the PMR group significantly increased their vagally mediated HRV compared to the active control group. However, the non-significant effect of the average RFT group can be caused by the fact that they had a significantly higher HRV compared to the active control group, which could not be further increased (cf. Schumann et al., 2019), or by the fact that the average RFT (daily for 5 minutes respectively) and PMR (three times a week for approximately 18 minutes respectively) intervention differed in frequency and duration, and the duration of a single average RFT session was too short.



*Figure 3.* Graphical overview of Study 3.

## ABSTRACT

Altogether Study 1 and Study 2 indicated that personality traits (here, action-state orientation) are an important factor and moderator when analyzing the association between different self-control variables or when analyzing possible indicators for state as well as trait self-control. Furthermore, Study 2 indicated that due to the multiple influences on HRV (cf. Fatissou et al., 2016; Laborde et al., 2018a), which can serve as an indicator of self-control capacity, it should best be studied in within-subject designs rather than in between-subject designs (cf. Quintana & Heathers, 2014). Finally, Study 3 deals with the possibility of increasing HRV by average RFT and PMR in healthy individuals. Here, PMR is shown to be effective, whereas the non-effectiveness of average RFT might be because the average RFT group generally had a significantly higher HRV (cf. Schumann et al., 2019) or that specific personality traits should also be taken into account in intervention studies. To sum it up, the three studies (for an overview of all studies, see Figure 4) extend the self-control and self-regulation research and shed some light on the maze of self-control and self-regulation.



*Figure 4.* Graphical overview of the expected associations for all three studies; only the interactions are shown.

## ABSTRACT

### References

- Bertsch, K., Hagemann, D., Naumann, E., Schachinger, H., & Schulz, A. (2012). Stability of heart rate variability indices reflecting parasympathetic activity. *Psychophysiology* 49, 672–682. <https://doi.org/10.1111/j.1469-8986.2011.01341.x>
- Diefendorff, J. M., Hall, R. J., Lord, R. G., & Streat, M. L. (2000). Action–state orientation: Construct validity of a revised measure and its relationship to work-related variables. *Journal of Applied Psychology*, 85, 250–263. <https://doi.org/10.1037/0021-9010.85.2.250>
- Fatissou, J., Oswald, V., & Lalonde, F. (2016). Influence diagram of physiological and environmental factors affecting heart rate variability: An extended literature overview. *Heart International*, 11, e32–e40. <https://doi.org/10.5301/heartint.5000232>
- Fischer, R., Plessow, F., Dreisbach, G., & Goschke, T. (2015). Individual differences in the context-dependent recruitment of cognitive control: Evidence from action versus state orientation. *Journal of Personality*, 83, 575–583. <https://doi.org/10.1111/jopy.12140>
- Gröpel, P., Baumeister, R. F., & Beckmann, J. (2014). Action versus state orientation and self-control performance after depletion. *Personality and Social Psychology Bulletin*, 40, 476–487. <https://doi.org/10.1177/0146167213516636>
- Holzman, J. B., & Bridgett, D. J. (2017). Heart rate variability indices as bio-markers of top-down self-regulatory mechanisms: A meta-analytic review. *Neuroscience & Biobehavioral Reviews*, 74, 233–255. <https://doi.org/10.1016/j.neubiorev.2016.12.032>
- Jostmann, N. B., & Koole, S. L. (2006). On the waxing and waning of working memory: Action orientation moderates the impact of demanding relationship primes on working memory capacity. *Personality and Social Psychology Bulletin*, 32, 1716–1728. <https://doi.org/10.1177/0146167206292595>
- Jostmann, N. B., & Koole, S. L. (2007). On the regulation of cognitive control: Action

## ABSTRACT

orientation moderates the impact of high demands in Stroop interference tasks. *Journal of Experimental Psychology: General*, *136*, 593–609. <https://doi.org/10.1037/0096-3445.136.4.593>

Koole, S. L., & Jostmann, N. B. (2004). Getting a grip on your feelings: Effects of action orientation and external demands on intuitive affect regulation. *Journal of Personality and Social Psychology*, *87*, 974–990. <https://doi.org/10.1037/0022-3514.87.6.974>

Koole, S. L., Jostmann, N. B., & Baumann, N. (2012). Do demanding conditions help or hurt self-regulation?. *Social and Personality Psychology Compass*, *6*, 328–346. <https://doi.org/10.1111/j.1751-9004.2012.00425.x>

Koole, S. L., Kuhl, J., Jostmann, N. B., & Vohs, K. D. (2005). On the hidden benefits of state orientation: Can people prosper without efficient affect regulation skills?. In A. Tesser, J. Wood, & D. A. Stapel (Eds.), *On building, defending, and regulating the self: A psychological perspective* (pp. 217–243). London, UK: Taylor & Francis.

Kotabe, H. P., & Hofmann, W. (2015). On integrating the components of self-control. *Perspectives on Psychological Science*, *10*, 618–638. <https://doi.org/10.1177/1745691615593382>

Kuhl, J. (1994a). A theory of action and state orientations. In J. Kuhl & J. Beckmann (Eds.), *Volition and personality: Action versus state orientation* (pp. 9–46). Göttingen, Germany: Hogrefe & Huber Publishers.

Kuhl, J. (1994b). Action versus state orientation: Psychometric properties of the Action Control Scale (ACS-90). In J. Kuhl & J. Beckmann (Eds.), *Volition and personality: Action versus state orientation* (pp. 47–59). Göttingen, Germany: Hogrefe & Huber Publishers.

Kuhl, J. (2000). A functional-design approach to motivation and self-regulation: The dynamics of personality systems interactions. In M. Boekaerts, P. R. Pintrich, & M. Zeidner (Eds.),

## ABSTRACT

*Handbook of self-regulation* (pp. 111–169). Burlington, MA: Elsevier/Academic Press.

<https://doi.org/10.1016/B978-012109890-2/50034-2>

Laborde, S., Mosley, E., & Mertgen, A. (2018a). A unifying conceptual framework of factors associated to cardiac vagal control. *Heliyon*, 4, e01002. <https://doi.org/10.1016/j.heliyon.2018.e01002>

Laborde, S., Mosley, E., & Mertgen, A. (2018b). Vagal tank theory: The three Rs of cardiac vagal control functioning—resting, reactivity, and recovery. *Frontiers in Neuroscience*, 12. <https://doi.org/10.3389/fnins.2018.00458>

Quintana, D. S., & Heathers, J. A. J. (2014). Considerations in the assessment of heart rate variability in biobehavioral research. *Frontiers in Psychology*, 5. <https://doi.org/10.3389/fpsyg.2014.00805>

Schumann, A., Köhler, S., Brotte, L., & Bär, K.-J. (2019). Effect of an eight-week smartphone-guided HRV-biofeedback intervention on autonomic function and impulsivity in healthy controls. *Physiological Measurement*, 40, 064001. <https://doi.org/10.1088/1361-6579/ab2065>

Segerstrom, S. C., & Nes, L. S. (2007). Heart rate variability reflects self-regulatory strength, effort, and fatigue. *Psychological Science*, 18, 275–281. <https://doi.org/10.1111/j.1467-9280.2007.01888.x>

Shaffer, F., & Ginsberg, J. P. (2017). An overview of heart rate variability metrics and norms. *Frontiers in Public Health*, 5. <https://doi.org/10.3389/fpubh.2017.00258>

Thayer, J. F., Åhs, F., Fredrikson, M., Sollers, J. J., & Wager, T. D. (2012). A meta-analysis of heart rate variability and neuroimaging studies: Implications for heart rate variability as a marker of stress and health. *Neuroscience & Biobehavioral Reviews*, 36, 747–756. <https://doi.org/10.1016/j.neubiorev.2011.11.009>

## ABSTRACT

- Thayer, J. F., Hansen, A. L., Saus-Rose, E., & Johnsen, B. H. (2009). Heart rate variability, prefrontal neural function, and cognitive performance: The neurovisceral integration perspective on self-regulation, adaptation, and health. *Annals of Behavioral Medicine*, *37*, 141–153. <https://doi.org/10.1007/s12160-009-9101-z>
- Thayer, J. F., & Lane, R. D. (2000). A model of neurovisceral integration in emotion regulation and dysregulation. *Journal of Affective Disorders*, *61*, 201–216. [https://doi.org/10.1016/s0165-0327\(00\)00338-4](https://doi.org/10.1016/s0165-0327(00)00338-4)
- Thayer, J. F., & Lane, R. D. (2009). Claude Bernard and the heart–brain connection: Further elaboration of a model of neurovisceral integration. *Neuroscience & Biobehavioral Reviews*, *33*, 81–88. <https://doi.org/10.1016/j.neubiorev.2008.08.004>
- Wolff, M., Krönke, K.-M., Venz, J., Kräplin, A., Bühringer, G., Smolka, M. N., & Goschke, T. (2016). Action versus state orientation moderates the impact of executive functioning on real-life self-control. *Journal of Experimental Psychology: General*, *145*, 1635–1653. <https://doi.org/10.1037/xge0000229>
- Zahn, D., Adams, J., Krohn, J., Wenzel, M., Mann, C. G., Gomille, L. K., Jacobi-Scherbening, V., & Kubiak, T. (2016). Heart rate variability and self-control—a meta-analysis. *Biological Psychology*, *115*, 9–26. <https://doi.org/10.1016/j.biopsycho.2015.12.007>

**GENERAL INTRODUCTION**

Do you sometimes have the urge or drive to eat too much candy, to spend the whole day on your smartphone and social media, to drink too much alcohol, to spend money without thinking about it, or to procrastinate work even if you are supposed to get something done to achieve your long-term goals<sup>2</sup>? It can feel like being pulled into opposite directions. Why do we sometimes manage not to give in to these impulses? The answer is that we can exercise self-control, which also contributes to many adaptive outcomes in society, including improved physical (also enhanced weight loss) and mental health, better problem-solving skills, and reduced susceptibility to drug abuse and delinquency (e.g., Mischel et al., 2011; Moffitt et al., 2011; Tangney et al., 2004; Wilfley et al., 2018). Therefore, self-control can be seen as a core aspect of adaptive human behavior, which is studied, largely in parallel, in the field of social and personality psychology (often assessed with report-based measurements of impulse control, motivation, and perseverance), cognitive psychology (often measured with performance-based tests), and even in biology<sup>3</sup> (e.g., Hofmann, Schmeichel, et al., 2012; Malanchini et al., 2019). Berkman and colleagues (2017) recently defined self-control as the process of selecting the most valued behavior when different options are available, by calculating a subjective value for each option through integrating various gains (e.g., money, social approval), and costs (e.g., effort, opportunity costs). Attention plays an important role in this process by gating the options entering the value process. However, this is only one way of defining self-control. In the course of this general introduction, further possibilities and perspectives of self-control are mentioned and discussed.

---

<sup>2</sup> Decisions involving tradeoffs among costs and benefits occurring at different time points are called intertemporal choices in neuroeconomics (see Kable, 2014, for combining the terms of intertemporal choices and self-control). Figner and colleagues (2010) used transcranial magnetic stimulation to show that the left lateral prefrontal cortex has an important role in intertemporal choices.

<sup>3</sup> In a recently published *meta-analysis*, Willems and colleagues (2019) concluded that 60 percent of self-control is hereditary.

## **1. Beginnings of self-control measurement and the importance of childhood self-control for future outcomes**

Previous studies measuring individual self-control differences used the Rorschach test and related projective methods (e.g., Singer, 1955). Subsequent studies, however, showed that these tests were not valid (e.g., Lilienfeld et al., 2000). In the 1960s, Walter Mischel developed the delay of gratification task, also known as the marshmallow experiment, to experimentally investigate self-control. In this performance task<sup>4</sup>, he made a tempting offer to four-year-old children: They could either eat one marshmallow immediately or two marshmallows if they managed to wait for 20 minutes without eating the first marshmallow. Some children immediately ate the marshmallow, whereas others chose to wait. Those who waited often showed fascinating strategies to delay satisfaction. Some covered the marshmallow with their hands while others covered their eyes, crawled under the table, looked away, and stared at the opposite wall (e.g., Mischel et al., 1972). The marshmallow experiment began as a small study that investigated how long preschool children (N = 653 children) could resist a small, instant reward to receive a greater reward later, and was then turned into a longitudinal study. Children who managed to initially resist the impulse to eat the marshmallow or avoid temptation, years later, showed higher academic, social, and health outcomes (e.g., Mischel et al., 1988; Mischel et al., 2011; Shoda et al., 1990). However, the follow-up investigations focused on much smaller sample sizes (Mischel et al., 1988 [N = 95 children]; Shoda et al., 1990 [N = 185 children]) than the initial delay of gratification task. Two conceptual replication studies based on a larger sample size of more than 900 children<sup>5</sup> only partly confirmed that the delay of gratification task had predictive power on later achievement for children because the magnitude of the association was much lower than in the original studies and highly sensitive to the inclusion of control variables (e.g., intelligence, family and sociodemographic characteristics; Duckworth et al.,

---

<sup>4</sup> For general pros and cons about performance tasks assessing behavior, see Duckworth and Yeager (2015).

<sup>5</sup> Longitudinal data from the National Institute of Child Health and Human Development.

## GENERAL INTRODUCTION

2013; Watts et al., 2018, they primarily focused on children whose mother had not completed college [n = 552]). Moreover, the dependency of the delay of gratification task on other variables was also exemplified in studies that highlighted the importance of the children's environment (i.e., beliefs about the reliability and stability of the world<sup>6</sup>), both short-term environmental impact, like the reliability of a researcher's verbal assurances (Kidd et al., 2013<sup>7</sup>), and longer-term environmental impact like the socioeconomic status of the children's parents (low socioeconomic status diminishes access to resources, and leads to harsher living conditions which reduce the likelihood of a future payoff; Sturge-Apple et al., 2016<sup>8</sup>). Furthermore, Doebel and Munakata (2018) recently showed that group processes also have an impact on how long children choose to wait in a delay of gratification task. When children believed that their in-group waited and their out-group did not, they waited longer. In sum, these results indicated that self-control is a rather adaptive behavior that strongly depends on the context and environmental conditions. Therefore, self-control does not necessarily always lead to children waiting patiently but must rather be seen as an adaptation to the environment to increase one's fitness under a specific local environmental condition (e.g., Sturge-Apple et al., 2016). This means that under some conditions and with certain personality traits it is difficult to measure self-control by looking at the waiting time in the delay of gratification task. However, this does not mean that children's self-control can not predict later outcomes but that it is rather important to measure self-control reliably. The fact that self-control can predict later outcomes was, for example, confirmed by a huge New Zealand cohort study that combined nine self-control questionnaire measurements (by researcher-observers, teachers, parents, and the children themselves) at the ages of 3, 5, 7, 9, and 11 years into a single highly reliable composite

---

<sup>6</sup> Ma and colleagues (2018) indicated that children waited longer in delay of gratification tasks when they had high levels of generalized trust.

<sup>7</sup> Children in the reliable condition waited significantly longer than those in the unreliable condition.

<sup>8</sup> In the context of high resource environments, higher levels of children's vagal tone (higher levels of vagal tone, would be a physiological index of self-control; for more information see the later section: Heart-rate variability) would predict higher delay of gratification (i.e., waiting for the reward), whereas in resource-poor environments (i.e., the context of poverty) higher vagal tone would predict shorter delay of gratification (i.e., taking the immediate reward).

measure which indicated that childhood self-control is a good predictor for physical health, substance dependence, personal finances, and criminal offenses in adolescence and adulthood ( $N = 1037$  at age three, and  $972$  at age 32). These results were also confirmed by an additional British twin study<sup>9</sup> ( $N = 509$  pairs) which indicated that siblings with lower self-control at the age of five years had poorer outcomes at the age of 12, despite the shared family background and even after controlling for sibling differences in intelligence (Moffitt et al., 2011). To sum up the importance of childhood self-control for later life outcomes, a recent *meta-analysis* (Robson et al., 2020) provided further evidence that self-control in childhood can predict achievement (e.g., school engagement, academic achievement, unemployment), interpersonal behaviors (e.g., social competency, aggressive, and criminal behavior), mental health and healthy living (e.g., physical illness; obesity, cigarette smoking, alcohol, and substance abuse) in later life (in many of these areas the effect sizes were small to medium).

## **2. Constructs, variables, and ratings to measure self-control and self-regulation**

Today, self-control is often used interchangeably to the term self-regulation. Other neighboring and similar constructs include: executive functioning, working memory, emotion, mood, and affect regulation, self-discipline, delay of gratification, willpower, effortful control, ego strength/depletion, inhibitory control, cognitive control, behavioral inhibition, risk-taking, temperament, grit, impulsivity, and delay discounting. In general, these constructs can be divided into three broad domains with general and domain-specific findings and claims: action regulation (i.e., goal-directed initiation of physical actions), affect/emotion regulation (i.e., goal-oriented regulation of affect/emotion in magnitude, duration, and intensity) and cognition regulation (i.e., goal-oriented modification of cognitive processes, such as attention and working memory; Nigg, 2017). Even though the different constructs can be divided into these

---

<sup>9</sup> Data of the Environmental-Risk Longitudinal Twin Study (second sample of the study of Moffitt et al., 2011).

three broad domains, using these terms interchangeably would lead to the jingle-jangle fallacy<sup>10</sup> – which can hinder scientific progress (e.g., Block, 1995; Milyavskaya et al., 2019). Therefore, it is also important to know how to differentiate between the constructs of self-control and self-regulation. A pretty good distinction between self-control and self-regulation was suggested by Gillebaart (2018), in which she took the TOTE model (Test-Operate-Test-Exit model; Carver & Scheier, 1981, 1982) as the basis of the distinction and stated that self-control is a component of self-regulation but not synonymous to it. In the TOTE-model the ‘Test’ phase consists of a comparison between the existing standard and the individual goal standard (desired end-state). If this comparison reveals a discrepancy, then the individual operates to reduce the discrepancy. The result of this ‘Operate’ phase then serves as input for the second ‘Test’ phase. The feedback loop is exited if the current standard is in line with the desired goal standard. Gillebaart (2018) defined the goal setting and the monitoring element as self-regulation and the ‘Operate’ element as self-control. Therefore, she concludes that self-regulation is broader than only simply controlling behavior, but rather provides the entire scaffolding for goal pursuit. Since it is not always easy to distinguish between the ‘Operate’ and the ‘Test’ phase, the words self-control and self-regulation are used interchangeably in this framework text, even though I am aware of the jingle-jangle fallacy. However, not only can a distinction be made between self-control and self-regulation but it should also be clear when using the term self-control whether one is referring to state or trait self-control (cf. Milyavskaya et al., 2019). State self-control is required when one is directly exposed to a certain temptation or impulse (like for example in the delay of gratification task), whereby the long-term use of state self-control (i.e., after frequent and recent use of self-control) leads to a depletion of self-control (also known as ego depletion; for more information see, 3.1.), which is reflected in a reduced ability to successfully resist

---

<sup>10</sup> The jingle fallacy (Thorndike, 1904) refers to the use of the same name when referring to different constructs (i.e., the erroneous assumptions that two different things are equal because they have the same name), whereas the jangle fallacy (Kelley, 1927) refers to the use of different names for equivalent or highly similar constructs (i.e., the erroneous assumptions that two identical things are different because they have different names).

automatic impulses (e.g., Baumeister et al., 1998, 2007). On the other hand, trait self-control is understood as the ability to exert inhibition of undesired temptations or impulses in general (e.g., Imhoff et al., 2014). However, trait self-control is not only a result of a better direct inhibition of temptations and impulses but also the result of the proactive development of temptation avoiding behavior (implementation and initiation of plans), often resulting in smart automatic habits (e.g., exercise every day after work; de Ridder et al., 2012; Ent et al., 2015; Gillebaart & Adriaanse, 2017; Gillebaart & de Ridder, 2015; Hofmann, Baumeister, et al., 2012).

### ***2.1. Trait self-control and impulsivity***

Focusing on the measurement of trait self-control there are several questionnaires<sup>11</sup> available, like the Self-Control Behavior Inventory (Fagen et al., 1975), the Self-Control Schedule (Rosenbaum, 1980), the Self-Control subscale of the California Personality Inventory (Gough, 1987), the Self-Control Questionnaire (Brandon et al., 1990), the adapted Kendall-Wilcox Inventory for self-management (Kendall & Williams, 1982; Wills et al., 1994), the Ego-Undercontrol Scale (Letzring et al., 2005), the Self-Control Scale (Tangney et al., 2004), the Low-Self Control Scale (Grasmick et al., 1993), and the Barratt Impulsiveness Scale (Patton et al., 1995). A *meta-analysis* of trait self-control measurements identified more than 100 self-report questionnaires on trait self-control but most of them have only been used sporadically and are outdated or target specific behaviors (e.g., health behavior, see Brandon et al., 1990) in specific populations (e.g., adolescents, see Kendall & Williams, 1982; clinical samples, see Rosenbaum, 1980) rather than assessing individual differences across broad behavioral domains in general populations (Duckworth & Kern, 2011). However, three of these trait self-control scales (for example items of these scales, see Table 1) have been used relatively frequently in a variety of populations and with different types of behavioral outcomes (de

---

<sup>11</sup> For general pros and cons of trait self-control questionnaires, see Duckworth and Yeager (2015).

## GENERAL INTRODUCTION

Ridder et al., 2012; Duckworth & Kern, 2011; Hoyle & Davisson, 2016): The Low-Self Control Scale<sup>12</sup> (Grasmick et al., 1993), which is often used in studies on deviant behavior, the Self-Control Scale<sup>13</sup> (Tangney et al., 2004), which generally examines cross-situational control over impulses (prevention and inhibition focus) but also the capacity to initiate desired behaviors (promotion and initiation focus; de Ridder et al., 2011; Hoyle & Davisson, 2016), and the Barratt Impulsiveness Scale<sup>14</sup> (Patton et al., 1995), which was designed to measure impulsiveness. The Barratt Impulsiveness Scale (Patton et al., 1995) can be structured into three second-order factors: the first factor is motor impulsivity, which describes the impulse of the moment, the second factor is non-planning, which reflects a lifestyle more oriented toward the present than toward the future, and the third factor is attention impulsivity, which reflects cognitive instability and impulsivity.

Table 1

*Example Items of the Three Relatively Frequently Used Self-Control Scales.*

Questionnaire	Example Item	Response Scale
Low-Self Control Scale (Grasmick et al., 1993)	<i>“I will try to get the things I want even when I know it’s causing problems for other people.”</i>	All items are answered on a 4-point scale (strongly disagree, disagree somewhat, agree somewhat, strongly agree).
Self-Control Scale (Tangney et al., 2004)	<i>“I am good at resisting temptation.”</i>	All items are answered on a 5-point scale (not at all to very much).
Barratt Impulsiveness Scale (Patton et al., 1995)	<i>“I do things without thinking.”</i>	All items are answered on a 4-point scale (rarely/never, occasionally, often, almost always/always).

A later study by Whiteside and Lynam (2001), which aimed at bringing the measures and conceptions of impulsivity into order, identified four factors of impulsivity which are

<sup>12</sup> A German version is available (Eifler & Seipel, 2001).

<sup>13</sup> There is also a brief version (Tangney et al., 2004) available and it also exists a German brief version (Bertrams & Dickhäuser, 2009).

<sup>14</sup> German Barratt Impulsiveness Scale–short version (BIS-15; Meule et al., 2011).

## GENERAL INTRODUCTION

referred to as the UPPS model: Negative urgency (U), which reflects the tendency to act rashly in response to distress or extreme negative affect, lack of premeditation (P) which reflects the tendency of disregarding possible consequences of actions, lack of perseverance<sup>15</sup> (P) which reflects the difficulty of staying focused on difficult and boring tasks, and sensation seeking (S) which reflects the tendency to seek out thrilling and stimulating experiences. Later, a fifth factor, called positive urgency (P), was added to the model, which reflects the tendency to engage in rash actions in response to extreme positive affect (Cyders et al., 2007; Cyders & Smith, 2007, 2008). After this addition, the model was called the UPPS-P model, which can be accessed via the UPPS-P Impulsive Behavior Scale (Lynam et al., 2007)<sup>16</sup>. One of the strengths of the UPPS-P model is that it also maps the individual facets of impulsivity to the factors of the five-factor (Big Five) personality model<sup>17</sup>, relating negative urgency to neuroticism, perseverance and planning to conscientiousness, and sensation-seeking to extraversion (e.g., Whiteside & Lynam, 2001). Other possible questionnaires measuring impulsivity include a questionnaire by Dickman (1990), that differentiates between functional and dysfunctional impulsivity, the Eysenck Impulsiveness Questionnaire I<sub>7</sub> (Eysenck et al., 1985)<sup>18</sup>, that differentiates between the factors of impulsiveness, venturesomeness, and empathy, and the Sensation Seeking Scales, Form V (SSS-V; Zuckerman et al., 1978 [basis version])<sup>19</sup>, that differentiates between the factors of thrill and adventure seeking, disinhibition, experience seeking, and boredom susceptibility.

---

<sup>15</sup> This factor seems to be in strong agreement with what is understood by grit, namely the perseverance and passion for long-term goals despite setbacks and failures (e.g., Duckworth et al., 2007; Duckworth & Gross, 2014). It is possible to measure grit with the Grit Scale (Duckworth et al., 2007; German version: Fleckenstein et al., 2014) which has 12 items, and with its short form, the Grit-S, which contains a subset of eight items (Duckworth & Quinn, 2009; German version: Schmidt et al., 2019).

<sup>16</sup> There are different German versions of the UPPS Impulsive Behavior Scale (Kämpfe & Mitte, 2009; Keye et al., 2009 [focus on a short version]; Schmidt et al., 2008).

<sup>17</sup> For more information on how self-control variables relate to personality, see Hoyle and Davison (2016).

<sup>18</sup> A German version is available (Eysenck et al., 1990).

<sup>19</sup> A German version of Form V is available (Beauducel et al., 2003).

## GENERAL INTRODUCTION

In addition to these self-reports of impulsivity, Stahl and colleagues (2014) tried to identify factors of behavioral impulsivity using experimental tasks. Here, they identified five factors (they are correlated) of behavioral impulsiveness (see Box 1 for the factors). However, due to the experimental tasks, they focus more on state components rather than on trait components of impulsiveness.

### **Box 1. Five Factors of Impulsivity (Stahl et al., 2014).**

#### **Stimulus interference**

Goal-irrelevant stimuli receive increased attention.

#### **Proactive interference**

Goal-irrelevant cognitions leading to difficulties in goal-directed behavior.

#### **Response interference**

Goal pursuit is impaired by (involuntarily) irrelevant response tendencies.

#### **Information sampling**

How much information is considered prior to the decision – much/little?

#### **Delay discounting**

A short-term reward is preferred over long-term goals.

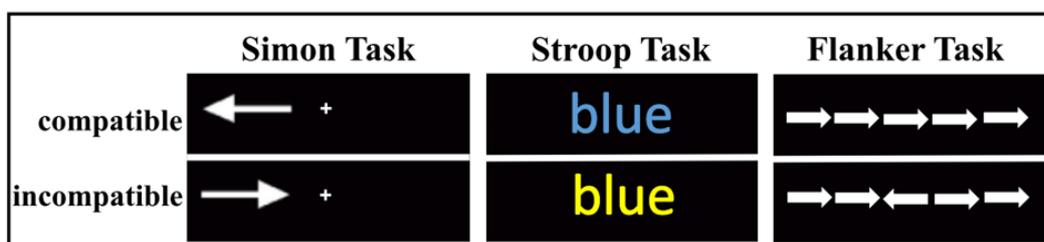
### **2.2. State self-control**

Focusing on the measurement of state self-control in social psychology, it is often detected by assessing self-control behavior in a specific task, for example in a taste rating task (e.g., drinking, eating) where the actual target quantity was the amount of intake (e.g., Muraven et al., 2002; Tice et al., 2001; Vohs & Heatherton, 2000), in a task that measures how long participants could continuously squeeze a handgrip (e.g., Muraven et al., 1998) in a difficult and frustrating persistence task (e.g., Baumeister et al., 1998; Clarkson et al., 2010), or a delay of gratification task (e.g., Mischel et al., 1972).

Furthermore, in cognitive psychology, state self-control is often detected by measuring cognitive control processes with conflict tasks, such as the Stroop, Flanker, or Simon task (e.g., Fischer et al., 2015; Friese & Wänke, 2014; Gailliot et al., 2007; Gröpel et al., 2014; see also

## GENERAL INTRODUCTION

Dang et al., 2017, for a *meta-analysis* using the Stroop task as a tool to measure state self-control capacity after depletion). In those conflict tasks, irrelevant stimulus information is intentionally used to slow down the processing of relevant stimulus information (see Figure 1 for an example of a Simon task, a Stroop task, or a Flanker task). A Simon task, for example, might look like this: Arrows are pointing to the left or the right and are presented on the left or the right of a fixation point. Participants must press a button to indicate the direction in which the arrow is pointing but ignore the position of the arrow. If the position of the arrow matches the direction that the arrow is pointing to, the condition is classified as compatible, otherwise as incompatible. The difference between incompatible trials and compatible trials is called interference effect (incompatible trials-compatible trials). Moreover, this interference effect is largely reduced or eliminated in trials following incompatible trials (conflict), compared to compatible ones (no conflict; e.g., Egner, 2007; Fischer et al., 2008; Gratton et al., 1992). This conflict-triggered reduction of the interference effect has been referred to as ‘conflict adaptation’ and is also called ‘Gratton effect’ because it was originally observed by Gratton and colleagues (1992), using a Flanker task (Botvinick et al., 2001). According to the conflict monitoring theory (Botvinick, 2007; Botvinick et al., 2001), and the adaption-by-binding model (Verguts & Notebaert, 2008, 2009), conflicts, which are registered as aversive signals (e.g., Dreisbach & Fischer, 2012; Fritz & Dreisbach, 2013), redirect the attentional focus to task-relevant features by diminishing the influence of task-irrelevant features. This leads to a reduction of the conflicts between these features and a faster response in the next incompatible trial.



*Figure 1.* Example of a Simon task, a Stroop task, or a Flanker task.

Moreover, it is also possible to measure state self-control with the help of questionnaires, for example with the State Self-Control Capacity Scale (SSCCS; Bertrams et al., 2011 [German version]; Ciarocco et al., 2007).

Regardless of which method is used to measure state self-control, it is often modeled by two opposing systems: A lower-order system ('hot' system) that quickly, involuntarily, and automatically responds to associative cues of the moment (guided by bottom-up attention), and a higher-order system ('cold' system) that deliberately, reflectively, and systematically responds and can only function when enough resources (e.g., energy, attention) are available (guided by top-down attention; e.g., Carver et al., 2009; Evans, 2008; Evans & Stanovich, 2013; Feldman Barrett et al., 2004; Kruglanski & Gigerenzer, 2011). According to the neural-systems model of self-regulation failure (Heatherton & Wagner, 2011), self-regulation failure occurs when the strength of an automatic (bottom-up) impulse exceeds the top-down capacity to regulate it. This depends on prefrontal functioning, which can be impaired either when self-regulatory resources are depleted, or due to drugs, alcohol, or brain damage. A variable which seems to reflect the type of capacity needed to use top-down attention more efficiently is working memory capacity (WMC), which is part of the executive functions (EFs; for more information see the next section, 2.3.): The more available WMC, the likelier it is to successfully engage in controlled top-down processes (e.g., Feldman Barrett et al., 2004; Hofmann et al., 2008; Kane et al., 2001; Neys, 2006; Soto et al., 2008).

### ***2.3. Executive functions***

Cognitive mechanisms that are supposed to support successful self-control and self-regulation are the EFs (also called executive control or cognitive control), which are primarily located in the prefrontal cortex and almost entirely genetic in origin (Botvinick & Braver, 2015; Friedman et al., 2008; Hofmann, Schmeichel, et al., 2012; Miyake & Friedman, 2012; for an introduction of EFs, see Diamond, 2013). Nonetheless, EFs are neither necessary nor sufficient

## GENERAL INTRODUCTION

for goal attainment: Individuals with poor EFs sometimes reach their goals, and individuals with excellent EFs sometimes fail to reach their goals (Berkman, 2016)<sup>20</sup>. In general, there is no consensus about the definition and classification of EFs (also, there is no agreement upon the form of measurement) but many lists of EFs feature response inhibition, formation and implementation of plans, switching between tasks, and maintenance of memory contents and updating thereof (e.g., Schmeichel & Tang, 2015). According to a well-accepted EFs taxonomy by Miyake and colleagues (2000), there are three basic EFs<sup>21</sup> (for a detailed description, see Table 3): working memory operations, such as the maintenance and updating of relevant information ('updating'), inhibition of impulses ('inhibition'), and mental set shifting ('shifting'). Miyake and Friedman (2012) extended this model of EFs (Miyake et al., 2000) by proposing inhibition as the central EF factor, which has a higher influence on the more specific factors of updating and shifting. However, this model only applies to adults. In general, EFs and the capacity of each of the three factors develop over time so that the first manifestations of the three-way structure can be found at the age of 15 (e.g., Lee et al., 2013; Willoughby et al., 2010 [they find a unidimensional structure at the age of three]). A recent systematic review and re-analysis of published measurement models of EFs indicated most often a one to two-factor model among preschoolers (no study identified a specific shifting factor), three-factor models among school-aged children, three-factor or nested factor models among adolescents and adults, and two-factor models among older adults (most older adult studies supported two-factor models, but there was also support for three-factor models; Karr et al., 2018).

Recently, Doebel (2020) published an article that encourages researchers to rethink EFs and its development from the factor structure thinking. She is an advocate for seeing EFs as skills of using control in the service of specific goals (i.e., children do not simply develop an

---

<sup>20</sup> Furthermore, if a task becomes a habit (i.e., is automatically more or less fulfilled), the cortical control passes on from prefrontal to subcortical regions, which can subserve task performances much more efficiently than the prefrontal cortex (Diamond, 2013).

<sup>21</sup> However, each of them does not represent an orthogonal construct.

## GENERAL INTRODUCTION

inhibitory process, for example, that they can apply across a wide range of situations), which activate mental content (e.g., knowledge and awareness, beliefs, values, norms, interests, and preferences, which in the factor structure view of EFs is rather a noise that must be controlled than skills that should be developed and supported) that children acquire with development (dependant on the socio-economic background; cf. Sturge-Apple et al., 2016) and that shape how individuals use control.

Sometimes EFs are also distinguished by the context in which they are used. When regulating motivationally and emotionally significant situations, EFs are called ‘hot’ EFs, whereas in more affectively neutral contexts they are often referred to as ‘cold’ EFs (e.g., Zelazo, & Carlson, 2012).

As seen in Table 3, the three basic EFs in adulthood (updating, inhibition, and shifting) are often measured by laboratory performance-based tasks<sup>22</sup>, but it is also possible to measure EFs by subjective ratings. The most commonly used rating scale of EFs (out of clinical settings), is the Behavior Rating Inventory of Executive Function (BRIEF; Gioia et al., 2003 [preschool version]<sup>23</sup>, Gioia et al., 2000 [school-aged students]<sup>24</sup>, Guy et al., 2005 [self-report version, age 13 to 18]<sup>25</sup>, Roth et al., 2005 [self-report version, age 18 to 90]).

---

<sup>22</sup> However, the EF tasks often do not exclusively tap on one EF, but also target other executive and non-executive processes.

<sup>23</sup> A German version is available (Daseking & Petermann, 2013).

<sup>24</sup> A German version is available (Drechsler & Steinhausen, 2013).

<sup>25</sup> A German version is available (Drechsler & Steinhausen, 2013).

## GENERAL INTRODUCTION

Table 2  
*Basic Executive Functions (EFs) and their Measure.*

Basic EFs	Definition	Experimental Measurement Examples
Updating/ Working Memory	Updating includes monitoring of information relevant for the current task and holding this information in mind, as well as the active manipulation of information that is currently held in the working memory (Diamond & Ling, 2016; Hofmann, Schmeichel, et al., 2012).	Updating is primarily reflected by a complex span task (commonly used in behavioral and cognitive psychology) or an <i>n</i> -back task (commonly used in cognitive neuroscience; e.g., Hofmann, Schmeichel, et al., 2012) <sup>26</sup> . In a complex span task, individuals have to complete a primary processing task (e.g., memorize words) while at the same time they have to engage in an interfering secondary task (e.g., verify a simple math problem). In an <i>n</i> -back task, individuals have to decide whether a stimulus matches with the stimulus <i>n</i> (e.g., 2) items back. Sometimes also a letter memory/digit span (backward) task is used. Here letters/numbers are shown and the participants have to remember the order (backward).
Inhibition	Inhibition describes the ability to suppress distracting stimuli and to resist spontaneous impulses that are incompatible with one's goal (Hofmann, Schmeichel, et al., 2012). Without inhibitory control, we would be at the mercy of impulses, thoughts, and habits that pull us this way or that way (Diamond & Ling, 2016).	Inhibition is typically assessed with a Go/NoGo task (a variation of this is the Stop-signal task) or a Stroop task (e.g., Hofmann, Schmeichel, et al., 2012). In a Go/NoGo task, individuals have to respond as quickly and as accurately as possible when the Go stimulus appears, and suppress their reaction when the NoGo stimulus appears. In a Stroop task, color words are written in different color ink than the word describes. Because reading is a more automatic process than color naming, individuals must inhibit reading to name the correct color ink of the word.
Shifting/ Cognitive Flexibility	Shifting describes the ability to switch back and forth between two different mental sets, or from one task to another (Miyake et al., 2000). If a way to solve a problem doesn't work, we need the shifting function to understand and tackle the problem from a different perspective (Diamond & Ling, 2016).	The shifting tasks are rather variable (cf. Karr et al., 2018). Here, it depends on the reorientation of attention from one set of features to another set, like in a task, where the target stimulus alternate between a number and a letter so that in one trial the number is the target stimulus and the letter the distractor and in the next trial it is vice versa. Also, the number-letter task is used relatively often. In this task, the screen is divided into four quarters by a horizontal and a vertical line. In each trial, a number-letter pair (e.g., 3a) is presented in the central corner of the quarters. Numbers are either even or odd (e.g., 2, 4 or 3, 5), and letters are either vowels or consonants (e.g., a, e or m, l). Participants are then instructed to indicate whether the number is even or odd when the stimulus is shown above the horizontal line and to indicate whether the letter is a vowel or a consonant when the stimulus is shown below the horizontal line (or vice versa).

<sup>26</sup> Redick and Lindsay (2013) indicate that both measures only correlate weak ( $r = .20$ ), which casts doubt on whether both types of tasks measure the same. However, Schmiedek and colleagues (2014) give a possible explanation for this low correlation. If measurement error and content-specific sources of variance were accounted for, latent factors of the complex span and the *n*-back task correlated with about  $r = .69$  in samples of younger as well as older adults. To sum it up, although each of the tasks has its own characteristics (the description of these goes beyond this general introduction), both can be used to measure WMC.

#### 2.4. *Heart rate variability*

Two major theories, the polyvagal theory (Porges, 2001, 2007) and the neurovisceral integration model (Thayer et al., 2009, 2012; Thayer & Lane, 2000, 2009)<sup>27</sup>, point to the vagally mediated heart rate variability (HRV; also called cardiac vagal control)<sup>28</sup> as a biomarker that provides information about individuals' emotional, attentional and cognitive self-regulation capacity. The vagally mediated HRV, which results from the parasympathetic activity<sup>29</sup> of the autonomic nervous system (ANS)<sup>30</sup>, in particular of the vagus nerve (also, via the stellate ganglia), influences the sinoatrial node (a small muscle strip in the upper part of the right atrium that is influenced by the neurotransmitter of norepinephrine [sympathetic influence] and acetylcholine [parasympathetic influence])<sup>31</sup>, the primary pacemaker of the heart leading to a reduced heart rate (HR) and increased intervals between two consecutive heartbeats (e.g., Appelhans & Luecken, 2006; Thayer et al., 2009, 2012). The ANS itself is primarily influenced by the Central Autonomic Network (CAN; e.g., Benarroch, 1993; Sklerov et al., 2018), which is an intricate network including the brainstem and certain forebrain regions<sup>32</sup>.

The evolutionary based polyvagal theory (Porges, 2001, 2007) assumes that apart from the sympathetic branch, supporting mobilization behavior (e.g., fight/flight response), two

---

<sup>27</sup> The neurovisceral integration model was recently updated and expanded by indicating an eight-level hierarchy of nervous system structure and describing the influence of each level to vagal control (Smith et al., 2017).

<sup>28</sup> There are three widely-used approaches for the analysis of HRV, the time-domain methods, the frequency-domain methods, and the non-linear methods. From these methods, of which the first two methods are most commonly used, are the following parameters recommended to identify vagally mediated resting HRV, respectively cardiac vagal control: root mean square of successive differences (RMSSD), peak-valley (time-domain properties of the Electrocardiogram signal) or high-frequency band (0.15-0.40 Hertz [Hz]; Laborde et al., 2017; Shaffer & Ginsberg, 2017).

<sup>29</sup> The heart is under tonic inhibitory control by parasympathetic influence (e.g., Thayer & Lane, 2009)

<sup>30</sup> Parasympathetic nerves exert their effects more rapidly (<1 second) than sympathetic nerves (>5 seconds; reaches a steady level in 20-30 seconds if the stimulus is continuous; e.g., Hainsworth, 1995; Nunan et al., 2010; Shaffer et al., 2014).

<sup>31</sup> Interestingly, the majority of fibers in the vagus nerve (approximately 85-90%) are afferents, and signals are sent to the brain (Cameron, 2002).

<sup>32</sup> More precisely the CAN includes the anterior cingulate, orbitofrontal and ventromedial prefrontal cortices, insular, the central nucleus of the amygdala, the paraventricular and related nuclei of the hypothalamus, the periaqueductal gray matter, the parabrachial nucleus, the nucleus of the solitary tract, the nucleus ambiguus, the ventrolateral medulla, the ventromedial medulla, and the medullary tegmental field (Thayer et al., 2009).

## GENERAL INTRODUCTION

vagus nerve types exist. The myelinated vagus branch enables regulatory behavior (e.g., self-control, emotion regulation; inhibition of physiological arousal, self-soothing) and, thus, promotes prosocial behavior (e.g., social communication, social engagement). The second type is the reptilian unmyelinated vagus branch, which can nearly stop the heart (massive bradycardia) and results in a ‘freeze’ response (i.e., shutdown behavior) if mobilization (i.e., fight/flight) behavior is not possible. Humans with low vagal tone (myelinated vagus) have less ability to prevent themselves from plunging into fight/flight/freeze behavior when confronted with demanding situations<sup>33</sup>. Thus, according to the theory, cardiac vagal control, refers to the ability to maintain homeostasis, and the responsiveness to changing demands (Porges, 2001, 2007). In line with the polyvagal theory (Porges, 2001, 2007), Schwerdtfeger and colleagues (2020) indicated that shyness was related to lower vagally mediated HRV. Moreover, these authors indicated that in shy individuals, low vagally mediated HRV increased during social interactions with close others (signal safety), but not with not so close individuals like colleagues and friends. Social support not only has a positive effect on vagally mediated HRV in shy individuals but also influences the negative effect that rumination has on the HRV. Here, Gerteis and Schwerdtfeger (2016) showed, that reduced HRV as a result of ruminant thoughts, can be circumvented in socially supportive situations presumably because the social engagement system is activated (cf. Porges, 2001, 2007).

The second theory, the neurovisceral integration model (Thayer et al., 2009, 2012; Thayer & Lane, 2000, 2009) posits that vagally mediated resting HRV is linked to self-regulation, EFs, health, stress, and emotion regulation, due to the ability of HRV to index activity in a flexible network of neural structures that are dynamically organized in response to environmental challenges (i.e., how well an individual adapts to changing environmental

---

<sup>33</sup> However, low parasympathetic activity (i.e., low vagal tone) does not necessarily imply a high sympathetic activity (high low-frequency power, 0.04-0.15 Hz, often reflects increased sympathetic activity; also the very low frequency band, <0.003-0.04 Hz is associated with sympathetic activity), and vice versa (for more information, see Ernst, 2017).

conditions). For example, the default response to uncertainty, novelty, and threat is the fight or flight response (i.e., here the sympathetic influence leads to a reduction in HRV), which is also related to the negativity bias, a phenomenon that describes the tendency to prioritize negative over positive information. A neuronal structure that is responsible for the rapid detection of potential threats and uncertainty is the amygdala which is under tonic inhibitory control of the prefrontal cortex. In safe contexts threat representations in the amygdala are inhibited by the prefrontal cortex. However, a prefrontal hypoactivity (i.e., a low function of the prefrontal cortex) leads to a lack of inhibitory sub-cortical neural processes and deficits in EFs (e.g., Thayer et al., 2009, 2012; Thayer & Lane, 2000, 2009).

In summary, both perspectives, the polyvagal theory (Porges, 2001, 2007) and the neurovisceral integration model (Thayer et al., 2009; Thayer & Lane, 2000, 2009), suggest that prefrontal cortical structures are bi-directionally connected to the heart via subcortical structures and the vagus nerve, so that EFs and HRV have a common neural basis – the prefrontal cortex.

### ***2.5. Association between different self-control variables and ratings, and their predictive power.***

Although the neurovisceral integration model (Thayer et al., 2009, 2012; Thayer & Lane, 2000, 2009) supports the association between EFs and HRV, the association between the performance in EF lab tasks and HRV does not seem to be as clear, since two recent *meta-analyses* only indicated small effect sizes between performance-based EF lab tasks and HRV ( $r = .09$ , 123 studies, Holzman & Bridgett, 2017;  $r = .15$ , 26 studies, Zahn et al., 2016). Also, when considering the association between performance-based EF lab tasks and behavior ratings of self-control (i.e., self-control questionnaires), a *meta-analysis* (Duckworth & Kern, 2011) only indicated a 95% confidence interval from .08 to .12 (51 samples,  $N = 3,922$ ) for the correlation. Furthermore, a recent mini *meta-analysis* ( $N = 2,641$ ; Saunders et al., 2018) also

## GENERAL INTRODUCTION

revealed a small-to-no association between performance-based inhibition lab tasks (Stroop and Flanker tasks) and a self-control questionnaire (Self-Control Scale; Tangney et al., 2004). This small association between performance-based lab tasks and self-report ratings is also consistent with findings analyzing the construct of impulsivity (e.g., Cyders & Coskunpinar, 2011; Stahl et al., 2014). One possible explanation might be that the performance-based lab tasks and questionnaires assess control in very different ways with different kinds of knowledge, beliefs, and values (e.g., performance-based lab tasks do not take specific task goals and the mental content activated with the task that seems to be important for real-world self-control behavior, into account; cf. Doebel, 2020). Another reason for the small association may be that self-report ratings, also to some degree depend on socially desirable responses (e.g., Tangney et al., 2004). With the focus on the EF tasks specifically, one reason can also be that the performance in EF lab tasks is also influenced by other factors than the pure task ability (true score), for example, by graphical and numerical perception, color processing, verbal articulation, or motivation (task-impurity problem = measurement errors that impure the true score; e.g., Duckworth & Yeager, 2015; Miyake & Friedman, 2012; Sharma et al., 2014). Another possibility is that EFs<sup>34</sup> may enable self-controlled behavior only if control is sufficiently mobilized when needed. This might also depend on personality traits, for example on the general ability to tick off errors instead of giving them further thought (Wolff et al. 2016). If you think this further, the EFs testing could be influenced by personality traits (e.g., the general tendency to error rumination could affect the EF task performance, if the EF task reports errors or errors are easily identifiable). Another reason for the small association between performance-based EF lab tasks and self-reports could be that EF tasks assess the performance in a specific and artificial situation, whereas self-report measures assess what individuals tend to do over time and across situations so that performance-based EF lab tasks are more like a state measurement than a trait

---

<sup>34</sup> Wolff and colleagues (2016) measured EFs on a latent variable basis.

## GENERAL INTRODUCTION

measurement (e.g., Cyders & Coskunpinar, 2011)<sup>35</sup>. Furthermore, the often low retest reliability (low stability) of lab tasks (i.e., surveys show greater test-retest reliability), also seems to indicate that these are rather a state measurement than a trait measurement (Enkavi et al., 2019)<sup>36</sup>. However, the low retest reliability and the relatively small associations between performance-based EF lab tasks and other self-control variables maybe because experimental lab tasks only become established when the between-subject variance is low (i.e., on the one hand, low reliability for individual differences but on the other hand, a robust effect)<sup>37</sup>. Therefore, to use performance-based EF lab tasks in correlational research is rather problematic, since, in correlational research, reliability refers to the extent to which a measurement consistently ranks individuals, whereas in experimental lab tasks a reliable effect is one that nearly always replicates (for example the Stroop effect; Dang et al., 2020; Hedge et al., 2018).

Although the correlations between different measures of self-control are rather low, they tend to predict positive outcomes in later childhood, adolescence, and adulthood to a similar extent (Robson et al., 2020). However, Eisenberg and colleagues (2019)<sup>38</sup> showed that behavioral tasks could not predict the variance of real-world self-controlled behavior, whereas surveys do so moderately well (here, it should be mentioned that both surveys and the real-world outcomes were self-reports in this study that may be susceptible to similar biases). They conclude that this result speaks against a coherent and general self-control construct. Dang and colleagues (2020) do not generally deny the predictive ability of behavioral tasks but conclude that performance-based lab tasks with low reliability resulting from low between-person variance are not suitable for individual difference research (i.e., they have poor predictive

---

<sup>35</sup> The association between state and trait is also rather ambiguous. Some studies indicate that high trait self-control is associated with greater state self-control (e.g., DeWall et al., 2007), whereas others detect the opposite result and interpret it in such a way that individuals with high trait self-control have less experience with direct self-control conflicts (e.g., Imhoff et al., 2014).

<sup>36</sup> High retest reliability is desirable for measures that measure traits.

<sup>37</sup> This is also known as the reliability paradox.

<sup>38</sup> This study consisted of 522 adult participants, each completing a battery composed of 37 behavioral tasks and 22 self-report surveys.

validity for real-life outcomes)<sup>39</sup>. However, Friedman and Banich (2019) describe that performance-based lab tasks are also capable of being highly reliable and thus also capable of predicting future outcomes when they are used at a latent variable level. They cite the study by Friedman and colleagues (2016), which finds a test-retest correlation of 0.86 to 1.0 over a 6-year interval from late adolescence to early adulthood, and a study by Gustavson and colleagues (2018), which finds a test-retest correlation of 0.97 to 0.98 over a 6-year interval in middle age. Focusing on these results, Friedman and Banich (2019) concluded that if EFs are examined and considered at a latent variable level, then both questionnaires and task-based measures are important to understand self-control and associated behavioral outcomes. The fact that self-control failures do not differ on a neural level, between a lab task as well as during real-life, was also shown by a recent functional magnetic resonance study that associated both, with a reduced modulation of neural value signals in the ventromedial prefrontal cortex (Krönke et al. 2020). However, it is generally shown that several lab tasks (this can also be a problem for the low predictive power of the delay of gratification task) and questionnaires have to be combined to be able to make reliable statements about real-life self-control and future outcomes (cf. Moffitt et al., 2011).

### **3. Theories and moderators of self-control and self-regulation**

#### ***3.1. Depletion of state self-control***

One famous model focusing on the depletion of state self-control is the strength model of self-control (e.g., Baumeister et al., 1998, 2007). This model proposes that the strength of state self-control depends on how frequently and recently people had resisted any previously occurred desires or impulses, showing less successful resistance at subsequent impulses or

---

<sup>39</sup> However, Dang and colleagues (2020) stated that these tasks can be used in within-subject designs to make short-term predictions. They refer to a study by Powell and colleagues (2017) who indicated in an experience sampling study that within-subject differences in a Go/Nogo task can predict snack consumption in the following hour.

drives when state self-control had been frequently and recently used. This state is also referred to as ego depletion, resembling muscular tiredness (e.g., Baumeister et al., 1998, 2007, 2018). The strength model of self-control assumes a global pool of state self-control, so that when state self-control is used in one area (e.g., the preparation of a forthcoming exam), it can have a negative effect on another area (e.g., eating the chocolate bar<sup>40</sup>; Hagger et al., 2010; Hofmann, Baumeister, et al., 2012; Muraven et al., 2002; Vohs & Heatherton, 2000). Gailliot and colleagues (2007) proposed that blood glucose is the element that filled the global state self-control pool. This means that performing a self-control task reduces the glucose level and, hence, the performance in subsequent self-control tasks. This proposal of an energy model and the data that support it have, however, been the subject of considerable scholarly debate and research. The reason being that subsequent studies found no or only small evidence that glucose level is influenced by or associated with self-control (e.g., Beedie & Lane, 2012; Finley et al., 2019; Kurzban, 2010; Kurzban et al., 2013; Lange & Eggert, 2014; Molden et al., 2012; Schimmack, 2012; Vadillo et al., 2016). Furthermore, the evidence for the phenomenon of energy reduction alone (including that glucose is an indication of willpower) is rather inconclusive (e.g., Carter et al., 2015; Friese et al., 2019; Hagger et al., 2016, Vadillo et al., 2016), even if hundreds of studies and *meta-analyses* support the phenomenon of ego depletion (Dang, 2018 [medium effect], Hagger et al., 2010 [medium to strong effect]). This is also supported by findings which show that the performance on a self-control task and the effect of glucose on state self-control depended on the subject's beliefs concerning willpower, and current fatigue (e.g., Clarkson et al., 2010; Job et al., 2013; Savani & Job, 2017<sup>41</sup>), questioning the phenomenon of simple energy reduction, and the role of glucose in ego depletion. Another

---

<sup>40</sup> Moreover, when self-regulation capacity is low and individuals are depleted, candy consumption was primarily predicted by automatic implicit candy attitudes rather than by explicit candy attitudes (i.e., for example, dietary restraints; Hofmann et al., 2007).

<sup>41</sup> Belief concerning willpower is also culturally determined. For example, individuals in the Indian cultural context believe that exerting self-control in one task can be energizing and can help them to exert self-control on subsequent tasks (Savani & Job, 2017).

## GENERAL INTRODUCTION

model, the resource allocation model of self-control (Beedie & Lane, 2012) takes this into account, arguing that the body has sufficient glucose to fuel mental processes in almost every situation. According to this model, people choose to allocate glucose according to motivational priorities and situational demands, so that the performance depends on motivational priorities rather than on the current state of glucose. Therefore, the role of glucose in association with state self-control can be seen as a motivational factor rather than a metabolic factor (e.g., Molden et al., 2012; Painelli et al., 2010). Further studies also showed that motivational factors can increase state self-control capacity and reduce the probability of ego depletion. These studies demonstrated that increasing intrinsic motivation to perform a task, as well as the provision of monetary or altruistic incentives, enhanced state self-control performance (Moller et al., 2006; Muraven et al., 2008; Muraven & Slassareva, 2003; Vohs et al., 2012)<sup>42</sup>. This was found to be true even when participants were only reminded of money (Boucher, & Kofos, 2012), or motivational primes were subconscious (Capa et al., 2013). Motivation may also be the reason for the reduced use of state self-control resources when participants knew that they would engage in a demanding task in the future (Muraven et al., 2006). The process model of ego depletion (Inzlicht & Schmeichel, 2012), is a model that takes the shift of motivation and attention into account to explain the effect of ego depletion (the predictions of this model and the strength model of self-control [e.g., Baumeister et al., 1998, 2007] are more or less the same on the behavioral level but differ in their explanation of why ego depletion occurs). These shifts are directed away from controlling impulses ('have-to' goals) toward finding gratification ('want-to' goals; Inzlicht et al., 2014). In this model, changes in motivation directly influence the operation of the attentional system that initiates control (Inzlicht & Schmeichel, 2012). A recent high-powered, preregistered study (Garrison et al., 2019) showed that ego depletion

---

<sup>42</sup> However, there are also studies that do not show this effect. For example, Wenzel and colleagues (2019) indicate in a within-person design using laboratory and ambulatory assessment that neither motivation nor affect has been sufficient to explain differences in ego depletion.

affects attention control and, thus, provides evidence for the process model of ego depletion (Inzlicht & Schmeichel, 2012).

Focusing on different theoretical accounts of self-control, Kelley and colleagues (2019) stated that the after-effects of self-control may influence reward-related processes (i.e., increase in reward responsivity) rather than self-control per se. Moreover, the authors speculated that self-control may temporarily reduce EFs, leading to an increase in reward responsivity and that individuals with high EFs do not have such an increase in reward responsivity because exercising self-control is easier and less aversive for them.

### ***3.2. Action-state orientation***

Some studies also point out that it is important to consider personality in studies of self-control capacity and fatigue, by focusing on demand-related action-state orientation (AOD-SOD; Hesitation Scale; also called decision-related action-state orientation; see Box 2 for item example). These studies indicate that AOD individuals are more successful when it comes to allocating cognitive resources under demanding conditions than SOD individuals, because they are more efficient at self-motivation, such as by up-regulating positive affect and self-generating rewarding incentives. It seems that AOD individuals become invigorated rather than depleted by performing self-regulatory activities because they can self-motivate themselves in demanding circumstances (e.g., Dang et al., 2014; Gröpel et al., 2014; Jostmann & Koole, 2007, 2009; Koole & Jostmann, 2004; Koole et al., 2012; Kuhl, 2000)<sup>43</sup>. SOD individuals, who are characterized by hesitation and indecisiveness, are more likely to have difficulties with self-generating positive affect and self-motivation which means, they struggle to put plans and decisions into action, even though their thoughts often revolve around unfinished intentions

---

<sup>43</sup> Further possibilities to increase state self-control capacity and to reduce the probability of ego depletion include implementation intentions (i.e., planning; Webb & Sheeran, 2003; for more information about implementation intentions, see the section, 4.3.), mindfulness meditation (Friese et al., 2012); positive affect (Tice et al., 2007), self-affirmation (Schmeichel & Vohs, 2009; for a review about self-affirmation and the long-lasting effects of this intervention, see Cohen & Sherman, 2014), and personal prayers (Friese & Wänke, 2014).

(Kuhl, 1994a, 1994b; Ruigendijk et al., 2018; Ruigendijk & Koole, 2014; Zeigarnik, 1927). Dang and colleagues (2014) indicated that the advantage of AOD individuals over SOD individuals is not (only) due to better self-motivation and positive affect regulation but (also) the effect of faster and better adaptation to self-control tasks (depletion task, as well as the following state self-control task) in general. They stated that their consideration was consistent with (a few) findings indicating that cognitive adaptation (enough time to adapt to the task) to the depletion task eliminated or reversed the ego depletion effect (Dang et al., 2013; Dewitte, 2009).

In general, AOD-SOD is one subscale of the Action Control Scale (ACS-90<sup>44</sup>; Kuhl, 1994a, 1994b), which is part of the Personality Systems Interaction Theory (e.g., Kuhl, 2000), focusing on two further aspects of action versus state orientation (see Box 2 for item examples): failure-related action-state orientation (AOF-SOF; Preoccupation Scale), and performance-related action-state orientation (AOP-SOP; Volatility Scale).

**Box 2. Item Examples of the Three Action Control Subscales (Kuhl, 1994b).**

**Preoccupation Scale (AOF-SOF)**

When I have lost something valuable and can't find it anywhere:

- A) I have a hard time concentrating on anything else. (SOF)
- B) I don't dwell on it. (AOF)

**Hesitation Scale (AOD-SOD)**

When I know I must finish something soon:

- A) I have to push myself to get started. (SOD)
- B) I find it easy to get it done and over with. (AOD)

**Volatility Scale (AOP-SOP)**

When I have learned a new and interesting game:

- A) I quickly get tired of it and do something else. (SOP)
- B) I can really get into it for a long time. (AOP)

---

<sup>44</sup> See Kuhl (1990) for the German version.

## GENERAL INTRODUCTION

Individuals with a disposition toward SOF can be characterized by a reduced ability to down-regulate negative affect and ruminative thoughts, claiming processing capacity in working memory, after being exposed to aversive events and conflicts. Contrarily, AOF individuals down-regulate negative affect and disengage from past failures or conflicts more efficiently, and therefore have less obstructive ruminative thoughts (e.g., Fischer et al., 2015; Kuhl, 1994a, 1994b; Wolff et al., 2016). This action allows them to effectively concentrate on the task at hand. For example, Fischer and colleagues (2015) indicated, that SOF individuals seem to be less efficient in the flexible and rapid adaptation to conflicts in a Simon task, which are demanding and aversive (e.g., Dreisbach & Fischer, 2012; Fritz & Dreisbach, 2013), by showing less ‘conflict adaptation’ than AOF individuals. Furthermore, Wolff and colleagues (2016) showed that EFs enable self-controlled behavior (measured by tracking real-life self-control failures during seven consecutive days via smartphone) only if control is sufficiently mobilized when needed, which depends on AOF-SOF. In general, AOF individuals can use their EFs more effectively for self-controlled behavior.

What characterizes individuals with an AOP tendency is that they tend to remain focused on activities until they are completed (task persistence), whereas SOP individuals tend to switch to different activities prematurely. Therefore, this dimension can also be labeled as performance-related action-state orientation (Kuhl, 1994a, 1994b). Over the last few years, there has been a tendency in empirical research to ignore this action-state dimension in research, because this AOP-SOP facet focuses on a different aspect (maintaining an activity) than the facets of AOD-SOD, and AOF-SOF (starting an activity), and the internal consistency of the scale was fairly low (e.g., Diefendorff et al., 2000<sup>45</sup>; Diefendorff et al., 2018; Kanfer et al., 1994; Kazén & Quirin, 2018).

---

<sup>45</sup> For example, Diefendorff and colleagues (2000) reported an internal consistency (Cronbach’s alpha) of .56 for AOP-SOP.

The common ground of all three scales is that action-oriented individuals have advantages in the implicit regulation of affect and attention under demanding conditions. However, in low-demanding situations, state-oriented individuals have no disadvantages, they can even outperform action-oriented individuals (for example, by downplaying the risk of an inappropriate form of action control). Furthermore, state-oriented individuals can also outperform action-oriented individuals when external support helps them to cope with demanding situations or stress (cf. Koole et al., 2005, 2012).

### ***3.3. Combination of variables to determine self-control***

A model that predicts self-control capacity by a combination of variables is the integrative theory of self-control (Kotabe & Hofmann, 2015), which focuses on the interaction between control capacity and control motivation. According to this model, control motivation is activated when desire (for a review of desire, see Hofmann & Van Dillen, 2012) and higher-order goals are incompatible. In this model, control capacity is represented by EFs (e.g., WMC), which all rely on the same depletable and restorable cognitive resource – direct attention (e.g., Kane & Engle, 2002; Kaplan & Berman, 2010)<sup>46</sup>, and together with control motivation specify control effort, the actual amount of mental energy an individual spends to achieve a goal (i.e., the self-control capacity). Due to the integrative theory of self-control (Kotabe & Hofmann, 2015), control effort also depends on additional moderators and are highest when:

- 1) *desire strength is high* since people allocate less effort to weak than strong desires (however, only until the desired strength is too high compared to one's potential control effort),

---

<sup>46</sup> Many studies indicated that WMC is a valid predictor of attention control since individuals with high WMC are much better able to ignore attention-grabbing distractors (e.g., Engle et al., 1999; Feldman Barrett et al., 2004; Fukuda & Vogel, 2009; Gaspar et al., 2016; Kane et al., 2001, Kane & Engle, 2003).

## GENERAL INTRODUCTION

2) *perceived skills are low* since otherwise people make overly confident judgments about their skills, and

3) *competing goals are absent* since otherwise control effort would be split between different goals.

Based on the polyvagal theory (Porges, 2001, 2007) and the neurovisceral integration model (Thayer et al., 2009; Thayer & Lane, 2000, 2009), the vagal tank theory (Laborde et al., 2018b) assumes that the control capacity variable in the integrative theory of self-control (Kotabe & Hofmann, 2015) can also be indexed by resting cardiac vagal control (i.e., vagally mediated HRV). This assumption is made by the vagal tank theory (Laborde et al., 2018b), since from a neuroanatomical perspective, the prefrontal cortex is primarily important for EFs, as well as involved in cardiac vagal control (e.g., Thayer et al., 2009). In addition to this theoretical perspective, Segerstrom and Nes (2007) already indicated that cardiac vagal control is an indicator of self-control strength, effort, and fatigue. However, cardiac vagal control is not a resource in itself but rather reflects how efficiently self-control resources are mobilized and used in different situations (Laborde et al., 2018b). Besides baseline resting cardiac vagal control, the vagal tank theory (between-subject analysis; Laborde et al., 2018b) also focuses on reactivity and recovery of cardiac vagal control (within-subject analysis of cardiac vagal control changes) to detect state self-regulation capacity. Thereby, reactivity represents the change between baseline and a specific event, whereas recovery represents the change between the event and the time point after the event (i.e., post-event). Focusing on reactivity, the vagal tank theory (Laborde et al., 2018b) states that both lower and higher vagal withdrawal can be facilitative when facing demands. When metabolic demands (e.g., fight/flight response, which often provokes a nearly complete vagal withdrawal) are important, a higher vagal withdrawal is associated to a better self-regulation performance, whereas in cases where the activity highly relies on EFs, a smaller withdrawal, or even an increase in cardiac vagal control during the

event would reflect better self-regulation capacity (more resources are available to meet the self-regulatory demands). Regarding recovery, the vagal tank theory (Laborde et al., 2018b) also distinguishes between two situations: a cardiac vagal control increase during the event, or a cardiac vagal control decrease during the event. If there is a vagal withdrawal during the event, a return to initial resting cardiac vagal control (or even higher) is an indication of better self-regulation capacity. However, if there is an increase in cardiac vagal control during the event, a longer cardiac vagal tone staying above the initial level indicates better self-regulation capacity. In summary, this means, that a higher post-event cardiac vagal control always indicates better self-regulation capacity.

#### **4. Training of self-control and self-regulation**

Anyone who wants to make progress or keep his status in today's performance- and consumption-oriented society, has to meet many 'have-to' tasks (cf. Inzlicht et al., 2014), which require self-regulation at least in one domain (action, affect/emotion or cognition regulation; cf. Nigg, 2017; e.g., eat less candy, exercise more to stay healthy and prevent obesity; work on a high-performance level to keep the job, or even to climb up the ladder; cope with the demands of different areas of life). A recent *meta-analysis* indicated that repeated self-control practice improves self-control with a small to medium effect size<sup>47</sup>, also showing that such training effects tended to be larger for self-control stamina as for strength, for studies with active control groups than inactive groups, males than females and if proponents of the strength model of self-control were authors of the study (Friese et al., 2017). Moreover, some possibilities of increasing self-control have already been mentioned in the previous sections (e.g., increase intrinsic motivation; prayer, self-affirmation, development of habits). Another option to improve and modify individual self-control seems to be, to help individuals reweighting the subjective value inputs during choice (improve the value of the goal and/or reduce the value of

---

<sup>47</sup> However, bias-corrected estimates indicate a smaller effect.

the goal inconsistent alternative; Berkman et al., 2017). To increase the value of a long-term goal, it is also certainly necessary that individuals are supported by interventions or environmental cues that help them to direct attention to long-term consequences, when confronted with real-life choice conflicts (i.e., future-directed thoughts during a conflict should be promoted; cf. Krönke et al., 2020). However, Milyavskaya and Inzlicht (2017) also suggest that the path to better self-control lies not in increasing self-control but in removing possible temptations.

In the following sections, the focus will be on the training of EFs (including working memory capacity), HRV, and action-state orientation. All of these variables were described in detail in the previous sections. But first of all, it is important to know that a distinction can be made between a practice effect, which is when the task performance gets better in one task if it repeated, and a training effect, which means that the task performance increases in other tasks, as well (near transfer, i.e., similar to the practice task, up to far transfer, i.e., further away from the practice task/untrained task), as compared to the practice task alone (Berkman, 2016). In general, the goal should be to achieve a training effect and not only a practice effect.

#### ***4.1. Executive functions (including working memory capacity)***

Today, there is a consensus around the fact that the EFs are formed on a life-long basis with strong changes during childhood, and that they can be improved (primarily in people with poor EFs) through diverse approaches (e.g., Brehmer et al., 2012; Diamond, 2013; Diamond & Ling, 2016), like computerized cognitive training (e.g., CogMed training, *n*-back training, complex span training), diverse physical activity (e.g., aerobic exercise with or without cognitive demands, resistance training, coordinative exercise with or without cognitive demands, and yoga), as well as kindergarten and school programs<sup>48</sup> (e.g., Tools of the Mind<sup>49</sup>

---

<sup>48</sup> Personal characteristics of people leading such programs can have effects on how beneficial a program is, but this has received little attention in the literature (Diamond & Ling, 2016).

<sup>49</sup> Bodrova & Leong, 2007; a similar German program is EMIL (Walk et al., 2018).

## GENERAL INTRODUCTION

and Promoting Alternative Thinking Strategies<sup>50</sup>). For all approaches, it is important to generally include the following three aspects: complexity, novelty, and diversity, even if not all of these approaches are equally effective (Diamond & Ling, 2016; Moreau & Conway, 2014; see Diamond & Ling, 2019a, 2019b, for a summary of intervention effectiveness). Aerobic exercise interventions (with more or less cognitive and motor skill demands), resistance training, and yoga seemed to have the weakest EF benefit (Diamond & Ling, 2019a, 2019b; Singh et al., 2018). However, opinions differ as to whether aerobic exercise is an effective method to improve EFs (cf. Hillman et al., 2008, 2018). These differences of opinion may result from the fact that up to this date, there are no studies that quantify the optimal duration of interventions. Perhaps, people need to freely choose aerobic activities and practice them for longer periods (perhaps years), or more frequently during the week than what is usually required by studies, because more training leads to better EF training results (Diamond & Ling, 2016). What is consistently found, however, is that people who are more physically active and have better aerobic fitness, have better EFs than those who are less physically active (e.g., Boucard et al., 2012 [only better inhibition]; Etnier et al., 2006; Hillmann et al., 2005; Scudder et al., 2014; Sibley & Etnier, 2003). However, this association might also be due to additional variables, which are also positively associated with physical exercises, like better sleep (e.g., Chennaoui et al., 2015), reduced stress level, and better mood (e.g., Haslacher et al., 2015; Heijnen et al., 2016; Rethorst et al., 2009), since EFs suffer most if people are stressed, not in good physical health (e.g., colds, not enough sleep<sup>51</sup>), sad, lonely (every person needs another person who believes in him/her), or feeling excluded (e.g., Baumeister, 2002, 2005; Bernier et al., 2013; Diamond & Ling, 2016; Liston et al., 2009; Schoofs et al., 2009; Shields et al., 2017). Therefore, interventions should also focus on the reduction of these adverse factors and not only on the direct task-based training of EFs, because the far transfer effect on to untrained

---

<sup>50</sup> Kusché & Greenberg, 1994.

<sup>51</sup> Sleep quality could buffer against poor EF skills for children from low-income homes (Wetter et al., 2019).

cognitive skills and even the near transfer effect seems to be narrow or does not even exist, which also generally questions, whether the training of a single EF has any effect on self-control (e.g., Diamond & Ling, 2016; De Simoni & von Bastian, 2018; Kassai et al., 2019; Melby-Lervåg & Hulme, 2013)<sup>52</sup>. For this reason, Doebel (2020) also recommends (primarily for children) to focus on the consideration of a specific goal of interest (talking about feelings instead of crying or hitting) and then improve the knowledge, norms, and values through value-based training (e.g., teaching children about the values of talking about feelings through language, stories, modeling, etc.), instead of directly exercising EF components. The idea of value-based training is in line with the proposals of Berkman and colleagues (2017) and Krönke and colleagues (2020) to improve self-control.

#### ***4.2. Heart rate variability***

Focusing on the option of increasing the HRV, it is important to know that although the HRV is relatively stable<sup>53</sup>, it can be influenced by many factors in the short term, as well as in the long run (Bertsch et al., 2012<sup>54</sup>; for reviews of person and environmental factors affecting HRV, see Fatisson et al, 2016 and Laborde et al., 2018a [very extensive and detailed review]). Some of these factors affecting HRV include physical activity (HRV is reduced after [intense] physical activity; even if the training took place the day before; Daly et al., 2014; Henje Blom et al., 2009; Stanley et al., 2013), food ingestion (digestion of food reduces the HRV; Lu et al., 1999), liquid intake (HRV increased after espresso, decaffeinated espresso, or water and the increase was lower after consumption of decaffeinated espresso, as compared to caffeinated espresso in habitual coffee consumers; Zimmermann-Viehoff et al., 2015), smoking/nicotine intake (reduced HRV; e.g., Daly et al., 2014; Sjoberg & Saint, 2011), (trait) positive affect

---

<sup>52</sup> The *meta-analysis* by Kassai and colleagues (2019) found a medium-sized near transfer effect for the three basic EFs, whereas a well-powered study by De Simoni and von Bastian (2018) found neither a near nor a far transfer effect of working memory.

<sup>53</sup> To a certain extent HRV is also genetically inheritable (Goloshaykin et al., 2017).

<sup>54</sup> They also indicated that about 40% of HRV measurement variance was due to occasion-specific effects, which also speaks for the variable character of the HRV.

(HRV and positive affect are associated in an upward spiral, meaning that improved (trait) positive affect regulation is reciprocally associated with enhanced HRV; Kok et al., 2013; Kok & Fredrickson, 2010; Lü et al., 2013; Oveis et al., 2009; Wang et al., 2013). Additionally, HRV is also influenced by age (HRV decreases with age, and the variation is greater among women; e.g., Abhishekh et al., 2013; Bonnemeier et al., 2003), sex (women generally have a higher HRV<sup>55</sup>; Koenig & Thayer, 2016), weight (obese people have a lower HRV; e.g., Karason et al., 1999), and respiration (HR increases upon inhalation and decreases upon exhalation, a phenomenon known as respiratory sinus arrhythmia [RSA]; e.g., Yasuma & Hayano, 2004). Quintana and Heathers (2014) pointed out that within-subject designs provided optimal experimental control for these personal and environmental factors, apart from direct detection and control of these factors.

One possibility of increasing HRV, in the long run, seems to be the average resonance frequency training (RFT), which aims at maximizing the HRV by teaching the individual to breathe at 0.1 Hz (6 breaths/minute)<sup>56</sup> to the point where breathing and the HR on average oscillate at the same resonance frequency (e.g., Gevirtz, 2013; Lehrer, 2013; Lehrer & Gevirtz, 2014; Lehrer et al., 2000; Vaschillo et al., 2006; for overviews of the psychophysiological mechanisms and effects of slow breathing techniques, see Schwerdtfeger et al., 2019, and Zaccaro et al., 2018). However, every individual generally has a unique resonance frequency breathing rate, typically ranging between 4.5 and 6.5 breaths per minute. This individual breathing rate can be identified by asking a person to breathe at 4.5, 5.0, 5.5, 6.0, and 6.5 breaths per minute during HRV recording to find the breathing rate that results in the largest changes

---

<sup>55</sup> However, HRV in women also differs depending on the menstrual cycle (parasympathetic nervous activity is predominant in the proliferative phase; Brar et al., 2015).

<sup>56</sup> Lin and colleagues (2014) indicated that slow breathing with both 6 and 5.5 breaths per minutes resulted in higher HRV indices compared to spontaneous breathing, but that 5.5 breaths per minute (here the inhalation-to-exhalation ratio of 5:5 is preferable to a ratio of 4:6) increases HRV indices even slightly more than 6 breaths per minutes.

in HRV (i.e., where the current HRV is highest; originally done with frequency analysis, but it also works with time-domain analysis; e.g., Lehrer et al., 2000, 2003; Vaschillo et al., 2006).

Several RFT studies have demonstrated that breathing at a rate of 0.1 Hz clinically improves symptoms of physical and mental disorders (for a summary, see Gevirtz, 2013), including asthma (e.g., Lehrer et al., 2004), Posttraumatic Stress Disorder (e.g., Tan et al., 2011; Zucker et al., 2009), and depression (e.g., Karavidas et al., 2007; Siepmann et al., 2008; Tatschl et al., 2020<sup>57</sup>). Most clinical studies exist for anxiety and cardiovascular diseases<sup>58</sup>, indicating a small to medium effect of RFT (Lehrer et al., 2020).

Another possible method to improve cardiovascular effects and, thus, HRV is progressive muscle relaxation (PMR; e.g., Jacobson, 1938), which teaches individuals to reduce their muscle tone. Since muscles are part of the sympathetic nervous system, the direct effect of PMR is the decrease of sympathetic arousal (i.e., the parasympathetic activity is indirectly increased through a reduction of sympathetic activity)<sup>59</sup>, whereas RFT directly aims at strengthening the parasympathetic component (Lehrer et al., 2020).

### ***4.3. Action-state orientation***

In general, action-state orientation refers to an individual's intuitive affect (positive and negative), and attention regulation ability, operating largely on implicit levels (e.g., Koole & Fockenberg, 2011; Koole & Jostmann, 2004; Kuhl, 1994a, 2000). Important explicit emotion/desire regulation strategies are (for a review of emotion regulation, see Gross, 2015):

- avoiding exposure to tempting situations or stimuli,

---

<sup>57</sup> Tatschl and colleagues (2020) showed that a 5-week RFT (additionally to the normal therapies) facilitated depression recovery during inpatient psychiatric rehabilitation. However, the additional antidepressant gains vanish during an one-year follow-up.

<sup>58</sup> Cardiovascular diseases, along with depressive disorders, are among the pathologies that affect HRV the most (Fatisson et al., 2016).

<sup>59</sup> However, decreased sympathetic tone is not always associated with increased parasympathetic tone and vice versa. Sometimes and under certain circumstances they change parallel (e.g., during the diving reflex when the head is under water; Ernst, 2017).

## GENERAL INTRODUCTION

- down-regulating desire through cognitive reappraisal (i.e., altering the cognitive appraisal of an event, idea, or feeling),
- promoting to accept (in a nonjudgmental way) the occurrence of a certain desire without necessarily acting on it, instead of suppressing the desire,
- identifying recurring desires and tackling them, for example, with the help of implementation intentions,
- and using precommitments (e.g., self-contracts or making the intention, which will tackle the respective desire public, to make it harder to disengage from it; cf. Hofmann & Vohs, 2016).

Training these explicit emotion regulation strategies, provide a way to increase self-regulation.

Focusing on the possibility of whether action-state orientation can be improved and, thus, the implicit affect and attention regulation ability, it is important to understand the origin of action-state orientation, which is well described by Kuhl (2018). He indicates that affect regulation is learned in childhood and must be supported externally, as long as the child has not learned to regulate affect. Parents or caregivers may do so by providing reassurance or solace when the child experiences negative affect, or by expressing encouragement when the child has lost positive affect, because of a difficult task, for instance. However, children can only learn affect regulation, if their self-system is active. This is only the case when they know that their needs are understood. Therefore, caregivers need to pay attention when the child expresses feelings and needs and then be emotionally present for the child. If the self-system is not active, children do not learn to regulate their affect by themselves, even if the caregiver successfully regulates their emotions. According to Kuhl (2018), children may have had a happy childhood, a parental home where they experienced much positive affect and laughter, but they never learned to regulate their affect by themselves, because they never felt like their needs were understood. In adulthood, these individuals still require external help to regulate their affect,

## GENERAL INTRODUCTION

because they did not learn to stop the unintentional perseverance of negative affect, and/or to initiate positive affect. Therefore, it is important for state-oriented individuals to have someone who understands them, sees their needs, and affectively supports them so that they can resolve many of their self-regulatory problems (Koole et al., 2005). In childhood, they developed a state-oriented attitude, but in adulthood, it may be still possible for them to develop an action-oriented mode, if they feel like their needs are understood (e.g., by a partner, therapist or mentor; e.g., Kaschel & Kuhl, 2004; Schulte et al., 1997). One further method to primarily strengthen the general implementation system, and especially that of SOD individuals, is by translating goal intentions (SOD individuals often seem to have many; e.g., *I intended to reach x*), which are defined as end states of desires, into implementation intentions (if-then plans). Implementation intentions specify the when, where, and how of the goal-directed behavior should be initiated (e.g., *if situation x occurs, I will perform the goal-directed response y*; Gollwitzer, 1999, 2014). Thus, implementation intentions facilitate the overcoming of the intention-behavior gap by associating the control of one's behavior to a specific situation. Once the situation takes place, the response is automatically initiated (e.g., *if I come home from work, then I will go running in the park*). Complementary to developing implementation intentions, it would also be beneficial to help SOD individuals adopt a more easygoing and relaxed attitude toward goal achievement, which reduces the probability of being overwhelmed by intentions since their thoughts often revolve around unfinished intentions and plans (Ruigendijk et al., 2018).

A short-term intervention to improve the regulation of negative affect and, thus, also the negative ruminative thoughts is, besides the long-term support of a therapist or mentor, self-affirmation (Koole et al., 1999). Koole and colleagues (1999) indicate that affirming an important aspect of one's self-concept can reduce the accessibility of failure-related cognitions. However, these self-affirmations do not work better for SOF individuals, but in general, and can also be applied by AOF individuals.

At the end of this section, it should be mentioned that a state-oriented mode does not only have negative effects but it also has benefits. Therefore, the recommendation to develop an action orientation must be considered with caution. For example, state-oriented individuals can even outperform action-oriented individuals under supportive and low-demanding conditions (e.g., Koole et al., 2005).

## 5. Overview of the studies

Based on the current state of research mentioned above and to shed some more light on aspects of the maze of self-control and self-regulation, three studies have been conducted, which are briefly described below.

### 5.1. Study 1: *Executive functions and heart rate variability*

Despite a considerable rationale for a relationship between the performance in EF lab tasks and vagally mediated resting HRV based on the neurovisceral integration model (Thayer et al., 2009; Thayer & Lane 2000, 2009), two recent *meta-analyses* only indicated small effect sizes between HRV and EFs ( $r = .09$ , 123 studies, Holzman & Bridgett, 2017;  $r = .15$ , 26 studies, Zahn et al., 2016). Study 1 examines, whether one of the reasons for the small effect sizes could be that some participants are unable to use all of their EFs for the EF task at hand when testing the EF capacity. For this reason, three EF tasks with different task characteristics (cognitive demands and error feedback) were conducted, and also the implicit affect and attention regulation was measured by individual differences in action-state orientation (AOF-SOF and AOP-SOP; Kuhl, 1994a, 1994b). The first EF task (shifting task) required high cognitive processing demands and included direct visual and acoustical error feedback. The second EF task (inhibition task) required low cognitive processing demands and included indirect error feedback, and the third EF task (updating task) required high cognitive processing demands and provided no error feedback.

Given the importance of action-state orientation concerning demanding tasks, the following assumptions were formed. For the two demanding tasks (shifting and updating task), a negative relationship between EF task (higher values indicating worse performance, since the used inverse efficiency score<sup>60</sup> is primarily based on response time [Bruyer & Brysbaert, 2011]) and resting HRV was assumed for action-oriented individuals, whereas a positive relationship was assumed for state-oriented individuals. Depending on the availability of error feedback, either the AOF-SOF subscale (for the shifting task), or the AOP-SOP subscale (for the updating task) was expected to be a potential moderating variable. Because of the reduced cognitive demand in the inhibition task (only a two stimuli task), error rumination, which is high in SOF individuals, might be useful in this task, as it helps to identify the target stimulus faster. Hence, for SOF individuals, a negative relationship between EF (higher values indicating worse performance) and resting HRV was expected. Contrary, the reverse association was expected for AOF individuals, since they show lower error rumination, which reflects a disadvantage in this low-demanding task (cf. Koole et al., 2005, 2012).

### ***5.2. Study 2: Self-control capacity***

Study 2 analyzed potential indicators for state self-control capacity (measured by a Simon task) after demanding EF tasks, as well as for trait self-control capacity (measured by the German brief version [Bertrams & Dickhäuser, 2009] of the Self-Control Scale [Tangney et al., 2004]) by focusing on the interplay between control capacity, and motivation (measured by AOD-SOD). As possible control capacity indicators, WMC, based on the integrative theory of self-control (Kotabe & Hofmann, 2015), as well as on cardiac vagal control (indicated by vagally mediated HRV), based on the vagal tank theory (Laborde et al., 2018b) are analyzed. Since the vagal tank theory (Laborde et al., 2018b) also makes a prediction regarding the recovery of cardiac vagal control, associating faster vagal recovery (higher post-event cardiac

---

<sup>60</sup> Response time/(1–error rate).

vagal control) with better self-regulation capacity, it was also expected that by combining the integrative theory of self-control (Kotabe & Hofmann, 2015) and the vagal tank theory (Laborde et al., 2018b), that primarily SOD individuals with low WMC would have a reduced vagal recovery after the demanding EF tasks.

### ***5.3. Study 3: Interventions to increase heart rate variability***

Last but not least, Study 3 examined, whether it is possible to increase HRV in healthy individuals through average RFT (5 minutes every day) or PMR (three times a week, for approximately 18 minutes) over 77 days. The effects were tested against an active control group that completed a dual-task consisting of a balance task with parallel cognitive tasks (three times a week for 20 minutes). HRV was measured by the participants themselves every morning while using a mobile device. Until now, only a small number of studies have investigated the effect of RFT on HRV among healthy individuals, and the effects found are inconsistent. Siepmann and colleagues (2008) found that a 6-session RFT (duration of one session was 25 minutes) did not increase HRV among healthy individuals, whereas Lehrer and colleagues (2003) showed that a 10-session RFT (duration of one session was 30 minutes) increased HRV among healthy individuals. Looking for studies that investigated the effect of PMR on HRV in healthy individuals, it appears that there are not many studies available. For example, Seckendorff (2009) indicated in his dissertation that a six-week training of PMR (6 x 60 minutes; under the guidance of a psychologist) did not have a significant effect on HR and HRV in healthy individuals. However, a recent study by Lin (2018) focused on both methods, RFT, and relaxation training (including PMR), indicating that both methods (one hour per week in the laboratory and 10 minutes of daily homework) caused HRV (was only measured at the beginning and end of the study) to increase among healthy individuals over four weeks. However, participants in the RFT group increased HRV to a slightly greater degree than participants in the relaxation group. Also, a recent study by Schumann and colleagues (2019),

indicated in an eight-week RFT intervention study [five sessions<sup>61</sup>; four sessions at home and one session in the laboratory]) that it is possible to increase HRV in healthy individuals through RFT.

Nevertheless, the study situation is rather poor, insufficient, and contradictory and no intervention study has measured HRV in its subjects daily (most intervention studies measured HRV only twice, baseline and post-intervention) so that the goal of this study was to bring more clarity as to whether it is possible to increase HRV among healthy individuals through intensive average RFT and PMR training (77 days) while measuring HRV daily.

## 6. References general introduction

- Abhishekh, H. A., Nisarga, P., Kisan, R., Meghana, A., Chandran, S., Trichur Raju, & Sathyaprabha, T. N. (2013). Influence of age and gender on autonomic regulation of heart. *Journal of Clinical Monitoring and Computing*, 27, 259–264. <https://doi.org/10.1007/s10877-012-9424-3>
- Appelhans, B. M., & Luecken, L. J. (2006). Heart rate variability as an index of regulated emotional responding. *Review of General Psychology*, 10, 229–240. <https://doi.org/10.1037/1089-2680.10.3.229>
- Brar, T. K., Singh, K. D., & Kumar, A. (2015). Effect of different phases of menstrual cycle on heart rate variability (HRV). *Journal of Clinical and Diagnostic Research*, 9, CC01–CC04. <https://doi.org/10.7860/JCDR/2015/13795.6592>
- Baumeister, R. F., Bratslavsky, E., Muraven, M., & Tice, D. M. (1998). Ego depletion: Is the active self a limited resource? *Journal of Personality and Social Psychology*, 74, 1252–1265. <https://doi.org/10.1037/0022-3514.74.5.1252>

---

<sup>61</sup> In their article the authors did not write how long a session lasted. On request, the authors reported that one session lasted 2 x 11 minutes.

## GENERAL INTRODUCTION

- Baumeister, R. F., DeWall, C. N., Ciarocco, N. J., & Twenge, J. M. (2005). Social exclusion impairs self-regulation. *Journal of Personality and Social Psychology, 88*, 589–604. <https://doi.org/10.1037/0022-3514.88.4.589>
- Baumeister, R. F., Tice, D. M., & Vohs, K. D. (2018). The strength model of self-regulation: Conclusions from the second decade of willpower research. *Perspectives on Psychological Science, 13*, 141–145. <https://doi.org/10.1177/1745691617716946>
- Baumeister, R. F., Twenge, J. M., & Nuss, C. K. (2002). Effects of social exclusion on cognitive processes: Anticipated aloneness reduces intelligent thought. *Journal of Personality and Social Psychology, 83*, 817–827. <https://doi.org/10.1037/0022-3514.83.4.817>
- Baumeister, R. F., Vohs, K. D., & Tice, D. M. (2007). The strength model of self-control. *Current Directions in Psychological Science, 16*, 351–355. <https://doi.org/10.1111/j.1467-8721.2007.00534.x>
- Beauducel, A., Strobel, A. & Brocke, B. (2003). Psychometrische Eigenschaften und Normen einer deutschsprachigen Fassung der Sensation Seeking-Skalen, Form V [Psychometric characteristics and standards of a German version of the Sensation Seeking Scales, Form V]. *Diagnostica, 49*, 61–72. <https://doi.org/10.1026//0012-1924.49.2.61>
- Benarroch, E. E. (1993). The central autonomic network: Functional organization, dysfunction, and perspective. *Mayo Clinic Proceedings, 68*, 988–1001. [https://doi.org/10.1016/s0025-6196\(12\)62272-1](https://doi.org/10.1016/s0025-6196(12)62272-1)
- Berkman, E. T. (2016). Self-regulation training. In K. D. Vohs & R. F. Baumeister (Eds.), *Handbook of self-regulation: Research, theory and applications* (3rd ed., pp. 440–457). New York, NY: Guilford Press.
- Berkman, E. T., Hutcherson, C. A., Livingston, J. L., Kahn, L. E., & Inzlicht, M. (2017). Self-control as value-based choice. *Current Directions in Psychological Science, 26*, 422–428.

<https://doi.org/10.1177/0963721417704394>

- Bernier, A., Beauchamp, M. H., Bouvette-Turcot, A.-A., Carlson, S. M., & Carrier, J. (2013). Sleep and cognition in preschool years: Specific links to executive functioning. *Child Development, 84*, 1542–1553. <https://doi.org/10.1111/cdev.12063>
- Bertrams, A., & Dickhäuser, O. (2009). Messung dispositioneller Selbstkontroll-Kapazität [Measurement of trait self-control capacity]. *Diagnostica, 55*, 2–10. <https://doi.org/10.1026/0012-1924.55.1.2>
- Bertrams, A., Unger, A., & Dickhäuser, O. (2011). Momentan verfügbare Selbstkontrollkraft–Vorstellung eines Messinstruments und erste Befunde aus pädagogisch-psychologischen Kontexten [State self-control–presentation of a measuring instrument and first findings from educational-psychological contexts]. *Zeitschrift für Pädagogische Psychologie, 25*, 185–196. <https://doi.org/10.1024/1010-0652/a000042>
- Bertsch, K., Hagemann, D., Naumann, E., Schachinger, H., & Schulz, A. (2012). Stability of heart rate variability indices reflecting parasympathetic activity. *Psychophysiology, 49*, 672–682. <https://doi.org/10.1111/j.1469-8986.2011.01341.x>
- Beedie, C. J., & Lane, A. M. (2012). The role of glucose in self-control: Another look at the evidence and an alternative conceptualization. *Personality and Social Psychology Review, 16*, 143–153. <https://doi.org/10.1177/1088868311419817>
- Block, J. (1995). A contrarian view of the five-factor approach to personality description. *Psychological Bulletin, 117*, 187–215. <https://doi.org/10.1037/0033-2909.117.2.187>
- Bodrova, E., & Leong, D. J. (2007). *Tools of the Mind: The Vygotskian approach to early childhood education* (2nd ed.). Columbus, OH: Merrill/Prentice Hall.
- Bonnemeier, H., Wiegand, U. K. H., Brandes, A., Kluge, N., Katus, H. A., Richardt, G., & Potratz, J. (2003). Circadian profile of cardiac autonomic nervous modulation in healthy

- subjects: Differing effects of aging and gender on heart rate variability. *Journal of Cardiovascular Electrophysiology*, *14*, 791–799. <https://doi.org/10.1046/j.1540-8167.2003.03078.x>
- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*, 624–652. <https://doi.org/10.1037/0033-295x.108.3.624>
- Botvinick, M. M. (2007). Conflict monitoring and decision making: Reconciling two perspectives on anterior cingulate function. *Cognitive, Affective, & Behavioral Neuroscience*, *7*, 356–366. <https://doi.org/10.3758/cabn.7.4.356>
- Botvinick, M., & Braver, T. (2015). Motivation and cognitive control: From behavior to neural mechanism. *Annual Review of Psychology*, *66*, 83–113. <https://doi.org/10.1146/annurev-psych-010814-015044>
- Boucard, G. K., Albinet, C. T., Bugajska, A., Bouquet, C. A., Clarys, D., & Audiffren, M. (2012). Impact of physical activity on executive functions in aging: A selective effect on inhibition among old adults. *Journal of Sport and Exercise Psychology*, *34*, 808–827. <https://doi.org/10.1123/jsep.34.6.808>
- Boucher, H. C., & Kofos, M. (2012). The idea of money counteracts ego depletion effects. *Journal of Experimental Social Psychology*, *48*, 804–810. <https://doi.org/10.1016/j.jesp.2012.02.003>.
- Brandon, J. E., Oescher, J., & Loftin, J. M. (1990). The self-control questionnaire: An assessment. *Health Values*, *14*, 3–9.
- Brehmer, Y., Westerberg, H., & Bäckman, L. (2012). Working-memory training in younger and older adults: Training gains, transfer, and maintenance. *Frontiers in Human Neuroscience*, *6*. <https://doi.org/10.3389/fnhum.2012.00063>

- Bruyer, R., & Brysbaert, M. (2011). Combining speed and accuracy in cognitive psychology: Is the inverse efficiency score (IES) a better dependent variable than the mean reaction time (RT) and the percentage of errors (PE)? *Psychologica Belgica*, *51*, 5–13. <https://doi.org/10.5334/pb-51-1-5>
- Cameron, O. G. (2002). *Visceral sensory neuroscience: Interoception*. New York, NY, US: Oxford University Press.
- Capa, R. L., Bouquet, C. A., Dreher, J.-C., & Dufour, A. (2013). Long-lasting effects of performance-contingent unconscious and conscious reward incentives during cued task-switching. *Cortex*, *49*, 1943–1954. <https://doi.org/10.1016/j.cortex.2012.05.018>
- Carter, E. C., Kofler, L. M., Forster, D. E., & McCullough, M. E. (2015). A series of meta-analytic tests of the depletion effect: Self-control does not seem to rely on a limited resource. *Journal of Experimental Psychology: General*, *144*, 796–815. <https://doi.org/10.1037/xge0000083>
- Carver, C. S., Johnson, S. L., & Joormann, J. (2009). Two-mode models of self-regulation as a tool for conceptualizing effects of the serotonin system in normal behavior and diverse disorders. *Current Directions in Psychological Science*, *18*, 195–199. <https://doi.org/10.1111/j.1467-8721.2009.01635.x>
- Carver, C. S., & Scheier, M. F. (1981). The self-attention-induced feedback loop and social facilitation. *Journal of Experimental Social Psychology*, *17*, 545–568. [https://doi.org/10.1016/0022-1031\(81\)90039-1](https://doi.org/10.1016/0022-1031(81)90039-1)
- Carver, C. S., & Scheier, M. F. (1982). Control theory: A useful conceptual framework for personality–social, clinical, and health psychology. *Psychological Bulletin*, *92*, 111–135. <https://doi.org/10.1037/0033-2909.92.1.111>
- Chennaoui, M., Arnal, P. J., Sauvet, F., & Léger, D. (2015). Sleep and exercise: A reciprocal

## GENERAL INTRODUCTION

issue? *Sleep Medicine Reviews*, 20, 59–72. <https://doi.org/10.1016/j.smr.2014.06.008>

Ciarocco, N. J., Twenge, J. M., Muraven, M. & Tice, D. M. (2007). *Measuring state self-control: Reliability, validity, and correlations with physical and psychological stress.*

Unpublished Manuscript, Monmouth University, NJ, USA.

Clarkson, J. J., Hirt, E. R., Jia, L., & Alexander, M. B. (2010). When perception is more than reality: The effects of perceived versus actual resource depletion on self-regulatory behavior. *Journal of Personality and Social Psychology*, 98, 29–46. <https://doi.org/10.1037/a0017539>

Cohen, G. L., & Sherman, D. K. (2014). The psychology of change: Self-affirmation and social psychological intervention. *Annual Review of Psychology*, 65, 333–371. <https://doi.org/10.1146/annurev-psych-010213-115137>

Cyders, M. A., & Coskunpinar, A. (2011). Measurement of constructs using self-report and behavioral lab tasks: Is there overlap in nomothetic span and construct representation for impulsivity? *Clinical Psychology Review*, 31, 965–982. <https://doi.org/10.1016/j.cpr.2011.06.001>

Cyders, M. A., & Smith, G. T. (2007). Mood-based rash action and its components: Positive and negative urgency. *Personality and Individual Differences*, 43, 839–850. <https://doi.org/10.1016/j.paid.2007.02.008>

Cyders, M. A., & Smith, G. T. (2008). Emotion-based dispositions to rash action: Positive and negative urgency. *Psychological Bulletin*, 134, 807–828. <https://doi.org/10.1037/a0013341>

Cyders, M. A., Smith, G. T., Spillane, N. S., Fischer, S., Annus, A. M., & Peterson, C. (2007). Integration of impulsivity and positive mood to predict risky behavior: Development and validation of a measure of positive urgency. *Psychological Assessment*, 19, 107–118.

<https://doi.org/10.1037/1040-3590.19.1.107>

Daly, M., Baumeister, R. F., Delaney, L., & MacLachlan, M. (2014). Self-control and its relation to emotions and psychobiology: Evidence from a day reconstruction method study. *Journal of Behavioral Medicine*, *37*, 81–93. <https://doi.org/10.1007/s10865-012-9470-9>

Dang, J. (2018). An updated meta-analysis of the ego depletion effect. *Psychological Research*, *82*, 645–651. <https://doi.org/10.1007/s00426-017-0862-x>

Dang, J., Björklund, F., & Bäckström, M. (2017). Self-control depletion impairs goal maintenance: A meta-analysis. *Scandinavian Journal of Psychology*, *58*, 284–293. <https://doi.org/10.1111/sjop.12371>

Dang, J., Dewitte, S., Mao, L., Xiao, S., & Shi, Y. (2013). Adapting to an initial self-regulatory task cancels the ego depletion effect. *Consciousness and Cognition*, *22*, 816–821. <https://doi.org/10.1016/j.concog.2013.05.005>

Dang, J., King, K. M., & Inzlicht, M. (2020). Why are self-report and behavioral measures weakly correlated? *Trends in Cognitive Sciences*, *24*, 267–269. <https://doi.org/10.1016/j.tics.2020.01.007>

Dang, J., Xiao, S., Shi, Y., & Mao, L. (2014). Action orientation overcomes the ego depletion effect. *Scandinavian Journal of Psychology*, *56*, 223–227. <https://doi.org/10.1111/sjop.12184>

Daseking, M. & Petermann, F. (2013). *BRIEF-P: Verhaltensinventar zur Beurteilung exekutiver Funktionen für das Kindergartenalter (BRIEF-P). Deutschsprachige Adaptation des behavior rating inventory of executive function—preschool version (BRIEF-P) von Gerard A. Gioia, Kimberly A. Espy & Peter K. Isquith [BRIEF-P: Behavioural inventory for the assessment of executive functions for the preschool age*

## GENERAL INTRODUCTION

(*BRIEF-P*). *German adaptation of the behavior rating inventory of executive function-preschool version (BRIEF-P) by Gerard A. Gioia, Kimberly A. Espy & Peter K. Isquith*. Bern: H. Huber.

de Ridder, D. T. D., de Boer, B. J., Lugtig, P., Bakker, A. B., & van Hooft, E. A. J. (2011). Not doing bad things is not equivalent to doing the right thing: Distinguishing between inhibitory and initiatory self-control. *Personality and Individual Differences, 50*, 1006–1011. <https://doi.org/10.1016/j.paid.2011.01.015>

de Ridder, D. T. D., Lensvelt-Mulders, G., Finkenauer, C., Stok, F. M., & Baumeister, R. F. (2012). Taking stock of self-control: A meta-analysis of how trait self-control relates to a wide range of behaviors. *Personality and Social Psychology Review, 16*, 76–99. <https://doi.org/10.1177/1088868311418749>

De Simoni, C., & von Bastian, C. C. (2018). Working memory updating and binding training: Bayesian evidence supporting the absence of transfer. *Journal of Experimental Psychology: General, 147*, 829–858. <https://doi.org/10.1037/xge0000453>

DeWall, C. N., Baumeister, R. F., Stillman, T. F., & Gailliot, M. T. (2007). Violence restrained: Effects of self-regulation and its depletion on aggression. *Journal of Experimental Social Psychology, 43*, 62–76. <https://doi.org/10.1016/j.jesp.2005.12.005>

Dewitte, S., Bruyneel, S., & Geyskens, K. (2009). Self-regulating enhances self-regulation in subsequent consumer decisions involving similar response conflicts. *Journal of Consumer Research, 36*, 394–405. <https://doi.org/10.1086/598615>

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135–168. <https://doi.org/10.1146/annurev-psych-113011-143750>

Diamond, A., & Ling, D. S. (2016). Conclusions about interventions, programs, and approaches for improving executive functions that appear justified and those that, despite much hype,

## GENERAL INTRODUCTION

do not. *Developmental Cognitive Neuroscience*, 18, 34–48.

<https://doi.org/10.1016/j.dcn.2015.11.005>

Diamond, A., & Ling, D. S. (2019a). Aerobic-exercise and resistance-training interventions have been among the least effective ways to improve executive functions of any method tried thus far. *Developmental Cognitive Neuroscience*, 37, 100572. <https://doi.org/10.1016/j.dcn.2018.05.001>

Diamond, A., & Ling, D.S. (2019b). Review of the evidence on, and fundamental questions surrounding efforts to improve executive functions, including working. In: Bunting, M., Novick, J., Dougherty, M., Engle, R.W. (Eds.), *An integrative approach to cognitive and working memory training: Perspectives from psychology, neuroscience, and human development* (pp. 143–431). Oxford University Press, New York, NY.

Dickman, S. J. (1990). Functional and dysfunctional impulsivity: Personality and cognitive correlates. *Journal of Personality and Social Psychology*, 58, 95–102. <https://doi.org/10.1037/0022-3514.58.1.95>

Diefendorff, J. M., Hall, R. J., Lord, R. G., & Streat, M. L. (2000). Action–state orientation: Construct validity of a revised measure and its relationship to work-related variables. *Journal of Applied Psychology*, 85, 250–263. <https://doi.org/10.1037/0021-9010.85.2.250>

Diefendorff, J. M., Richard, E. M., Dinh, P. V., & LeNoble, C. (2018). Action-state orientation at work: Dynamic effects in organizational contexts. In N. Baumann, M. Kazén, M. Quirin, & S. L. Koole (Eds.), *Why people do the things they do: Building on Julius Kuhl's contributions to the psychology of motivation and volition* (pp. 302–321). Göttingen, Germany: Hogrefe.

Doebel, S. (2020). Rethinking executive function and its development. *Perspectives on Psychological Science*, 15, 942–956. <https://doi.org/10.1177/1745691620904771>

## GENERAL INTRODUCTION

- Doebel, S., & Munakata, Y. (2018). Group influences on engaging self-control: Children delay gratification and value it more when their in-group delays and their out-group doesn't. *Psychological Science*, 29, 738–748. <https://doi.org/10.1177/0956797617747367>
- Drechsler, R., & Steinhausen, H.-C. (2013). *BRIEF: Verhaltensinventar zur Beurteilung exekutiver Funktionen. Deutschsprachige Adaptation des behavior rating inventory of executive function (BRIEF) von G. A. Gioia, P. K. Isquith, S. C. Guy & L. Kennworthy und der self-report-version (BRIEF-SR) von S. C. Guy, P. K. Isquith & G. A. Gioia [BRIEF: Behavioural inventory for the assessment of executive functions. German adaptation of the behavior rating inventory of executive function (BRIEF) by G. A. Gioia, P. K. Isquith, S. C. Guy & L. Kennworthy and the self-report version (BRIEF-SR) by S. C. Guy, P. K. Isquith & G. A. Gioia]*. Bern: H. Huber.
- Dreisbach, G., & Fischer, R. (2012). Conflicts as aversive signals. *Brain and Cognition*, 78, 94–98. <https://doi.org/10.1016/j.bandc.2011.12.003>
- Duckworth, A., & Gross, J. J. (2014). Self-control and grit. *Current Directions in Psychological Science*, 23, 319–325. <https://doi.org/10.1177/0963721414541462>
- Duckworth, A. L., & Kern, M. L. (2011). A meta-analysis of the convergent validity of self-control measures. *Journal of Research in Personality*, 45, 259–268. <https://doi.org/10.1016/j.jrp.2011.02.004>
- Duckworth, A. L., Peterson, C., Matthews, M. D., & Kelly, D. R. (2007). Grit: Perseverance and passion for long-term goals. *Journal of Personality and Social Psychology*, 92, 1087–1101. <https://doi.org/10.1037/0022-3514.92.6.1087>
- Duckworth, A. L., & Quinn, P. D. (2009). Development and validation of the Short Grit Scale (Grit-S). *Journal of Personality Assessment*, 91, 166–174. <https://doi.org/10.1080/00223890802634290>

## GENERAL INTRODUCTION

- Duckworth, A. L., Tsukayama, E., & Kirby, T. A. (2013). Is it really self-control? Examining the predictive power of the delay of gratification task. *Personality and Social Psychology Bulletin, 39*, 843–855. <https://doi.org/10.1177/0146167213482589>
- Duckworth, A. L., & Yeager, D. S. (2015). Measurement matters: Assessing personal qualities other than cognitive ability for educational purposes. *Educational Researcher, 44*, 237–251. <https://doi.org/10.3102/0013189x15584327>
- Egner, T. (2007). Congruency sequence effects and cognitive control. *Cognitive, Affective, & Behavioral Neuroscience, 7*, 380–390. <https://doi.org/10.3758/cabn.7.4.380>
- Eifler, S., & Seipel, C. (2001). *Eine deutsche Version einer Skala zur Erfassung von Self-Control [A German version of a scale for recording self-control]* (Bielefelder Arbeiten zur Sozialpsychologie, 199). Bielefeld: Universität Bielefeld, Fak. für Soziologie.
- Eisenberg, I. W., Bissett, P. G., Zeynep Enkavi, A., Li, J., MacKinnon, D. P., Marsch, L. A., & Poldrack, R. A. (2019). Uncovering the structure of self-regulation through data-driven ontology discovery. *Nature Communications, 10*, 2319. <https://doi.org/10.1038/s41467-019-10301-1>
- Engle, R. W., Kane, M. J., & Tuholski, S. W. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 102–134). New York, NY, US: Cambridge University Press.
- Enkavi, A. Z., Eisenberg, I. W., Bissett, P. G., Mazza, G. L., MacKinnon, D. P., Marsch, L. A., & Poldrack, R. A. (2019). Large-scale analysis of test-retest reliabilities of self-regulation measures. *Proceedings of the National Academy of Sciences, 116*, 5472–5477. <https://doi.org/10.1073/pnas.1818430116>

## GENERAL INTRODUCTION

- Ent, M. R., Baumeister, R. F., & Tice, D. M. (2015). Trait self-control and the avoidance of temptation. *Personality and Individual Differences, 74*, 12–15. <https://doi.org/10.1016/j.paid.2014.09.031>
- Ernst, G. (2017). Heart-rate variability—more than heart beats? *Frontiers in Public Health, 5*. <https://doi.org/10.3389/fpubh.2017.00240>
- Etnier, J. L., Nowell, P. M., Landers, D. M., & Sibley, B. A. (2006). A meta-regression to examine the relationship between aerobic fitness and cognitive performance. *Brain Research Reviews, 52*, 119–130. <https://doi.org/10.1016/j.brainresrev.2006.01.002>
- Evans, J. St. B. T. (2008). Dual-processing accounts of reasoning, judgment, and social cognition. *Annual Review of Psychology, 59*, 255–278. <https://doi.org/10.1146/annurev.psych.59.103006.093629>
- Evans, J. St. B. T., & Stanovich, K. E. (2013). Dual-process theories of higher cognition. *Perspectives on Psychological Science, 8*, 223–241. <https://doi.org/10.1177/1745691612460685>
- Eysenck, S. B. G., Pearson, P. R., Easting, G., & Allsopp, J. F. (1985). Age norms for impulsiveness, venturesomeness and empathy in adults. *Personality and Individual Differences, 6*, 613–619. [https://doi.org/10.1016/0191-8869\(85\)90011-x](https://doi.org/10.1016/0191-8869(85)90011-x)
- Eysenck, S. B., Daum, I., Schugens, M. M., & Diehl, J. M. (1990). A cross-cultural study of impulsiveness, venturesomeness and empathy: Germany and England. *Zeitschrift für Differentielle und Diagnostische Psychologie, 11*, 209–213.
- Fagen, S. A., Long, N. J., & Stevens, D. J. (1975). *Teaching children self-control: Preventing emotional and learning problems in the elementary school*. Columbus, OH: Charles E. Merrill.
- Fatissou, J., Oswald, V., & Lalonde, F. (2016). Influence diagram of physiological and

## GENERAL INTRODUCTION

- environmental factors affecting heart rate variability: An extended literature overview. *Heart International*, *11*, e32–e40. <https://doi.org/10.5301/heartint.5000232>
- Feldman Barrett, L., Tugade, M. M., & Engle, R. W. (2004). Individual differences in working memory capacity and dual-process theories of the mind. *Psychological Bulletin*, *130*, 553–573. <https://doi.org/10.1037/0033-2909.130.4.553>
- Figner, B., Knoch, D., Johnson, E. J., Krosch, A. R., Lisanby, S. H., Fehr, E., & Weber, E. U. (2010). Lateral prefrontal cortex and self-control in intertemporal choice. *Nature Neuroscience*, *13*, 538–539. <https://doi.org/10.1038/nn.2516>
- Finley, A. J., Tang, D., & Schmeichel, B. J. (2019). Sweet nothings: No effects of self-control exertion on blood glucose levels. *Social Psychology*, *50*, 322–331. <https://doi.org/10.1027/1864-9335/a000376>
- Fischer, R., Dreisbach, G., & Goschke, T. (2008). Context-sensitive adjustments of cognitive control: Conflict-adaptation effects are modulated by processing demands of the ongoing task. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *34*, 712–718. <https://doi.org/10.1037/0278-7393.34.3.712>
- Fischer, R., Plessow, F., Dreisbach, G., & Goschke, T. (2015). Individual differences in the context-dependent recruitment of cognitive control: Evidence from action versus state orientation. *Journal of Personality*, *83*, 575–583. <https://doi.org/10.1111/jopy.12140>
- Fleckenstein, J., Schmidt, F. T. C., & Möller, J. (2014). Wer hat biss? Beharrlichkeit und beständiges Interesse von Lehramtsstudierenden; Eine deutsche Adaptation der 12-Item Grit Scale [Who's got grit? Perseverance and consistency of interest in pre-service teachers. A German adaptation of the 12-item Grit Scale]. *Psychologie in Erziehung und Unterricht*, *61*, 281–286. <https://doi.org/10.2378/peu2014.art22d>
- Friedman, N. P., & Banich, M. T. (2019). Questionnaires and task-based measures assess

different aspects of self-regulation: Both are needed. *Proceedings of the National Academy of Sciences*, *116*, 24396–24397. <https://doi.org/10.1073/pnas.1915315116>

Friedman, N. P., Miyake, A., Altamirano, L. J., Corley, R. P., Young, S. E., Rhea, S. A., & Hewitt, J. K. (2016). Stability and change in executive function abilities from late adolescence to early adulthood: A longitudinal twin study. *Developmental Psychology*, *52*, 326–340. <https://doi.org/10.1037/dev0000075>

Friedman, N. P., Miyake, A., Young, S. E., DeFries, J. C., Corley, R. P., & Hewitt, J. K. (2008). Individual differences in executive functions are almost entirely genetic in origin. *Journal of Experimental Psychology: General*, *137*, 201–225. <https://doi.org/10.1037/0096-3445.137.2.201>

Friese, M., Frankenbach, J., Job, V., & Loschelder, D. D. (2017). Does self-control training improve self-control? A meta-analysis. *Perspectives on Psychological Science*, *12*, 1077–1099. <https://doi.org/10.1177/1745691617697076>

Friese, M., Loschelder, D. D. D., Gieseler, K., Frankenbach, J., & Inzlicht, M. (2019). Is ego depletion real? An analysis of arguments. *Personality and Social Psychology Review*, *23*, 107 – 131. <https://doi.org/10.1177/1088868318762183>

Friese, M., Messner, C., & Schaffner, Y. (2012). Mindfulness meditation counteracts self-control depletion. *Consciousness and Cognition*, *21*, 1016–1022. <https://doi.org/10.1016/j.concog.2012.01.008>

Friese, M., & Wänke, M. (2014). Personal prayer buffers self-control depletion. *Journal of Experimental Social Psychology*, *51*, 56–59. <https://doi.org/10.1016/j.jesp.2013.11.006>

Fritz, J., & Dreisbach, G. (2013). Conflicts as aversive signals: Conflict priming increases negative judgments for neutral stimuli. *Cognitive, Affective, & Behavioral Neuroscience*, *13*, 311–317. <https://doi.org/10.3758/s13415-012-0147-1>

## GENERAL INTRODUCTION

- Fukuda, K., & Vogel, E. K. (2009). Human variation in overriding attentional capture. *Journal of Neuroscience*, *29*, 8726–8733. <https://doi.org/10.1523/jneurosci.2145-09.2009>
- Gailliot, M. T., Baumeister, R. F., DeWall, C. N., Maner, J. K., Plant, E. A., Tice, D. M., Brewer, L. E., & Schmeichel, B. J. (2007). Self-control relies on glucose as a limited energy source: Willpower is more than a metaphor. *Journal of Personality and Social Psychology*, *92*, 325–336. <https://doi.org/10.1037/0022-3514.92.2.325>
- Garrison, K. E., Finley, A. J., & Schmeichel, B. J. (2019). Ego depletion reduces attention control: Evidence from two high-powered preregistered experiments. *Personality and Social Psychology Bulletin*, *45*, 728–739. <https://doi.org/10.1177/0146167218796473>
- Gaspar, J. M., Christie, G. J., Prime, D. J., Jolicœur, P., & McDonald, J. J. (2016). Inability to suppress salient distractors predicts low visual working memory capacity. *Proceedings of the National Academy of Sciences*, *113*, 3693–3698. <https://doi.org/10.1073/pnas.1523471113>
- Gerteis, A. K. S., & Schwerdtfeger, A. R. (2016). When rumination counts: Perceived social support and heart rate variability in daily life. *Psychophysiology*, *53*, 1034–1043. <https://doi.org/10.1111/psyp.12652>
- Gevirtz, R. (2013). The promise of heart rate variability biofeedback: Evidence-based applications. *Biofeedback*, *41*, 110–120. <https://doi.org/10.5298/1081-5937-41.3.01>
- Gillebaart, M. (2018). The “operational” definition of self-control. *Frontiers in Psychology*, *9*. <https://doi.org/10.3389/fpsyg.2018.01231>
- Gillebaart, M., & Adriaanse, M. A. (2017). Self-control predicts exercise behavior by force of habit, a conceptual replication of Adriaanse et al. (2014). *Frontiers in Psychology*, *8*. <https://doi.org/10.3389/fpsyg.2017.00190>
- Gillebaart, M., & de Ridder, D. T. D. (2015). Effortless self-control: A novel perspective on

## GENERAL INTRODUCTION

- response conflict strategies in trait self-control. *Social and Personality Psychology Compass*, 9, 88–99. <https://doi.org/10.1111/spc3.12160>
- Gioia, G.A., Espy, K.A., & Isquith, P.K. (2003). *Behavior rating inventory of executive function—preschool version*. Odessa, Florida: Psychological Assessment Resources.
- Gioia, G.A., Isquith, P.K., Guy, S.C., & Kenworthy, L. (2000). *Behavior rating inventory of executive function*. Odessa, Florida: Psychological Assessment Resources.
- Gollwitzer, P. M. (1999). Implementation intentions: Strong effects of simple plans. *American Psychologist*, 54, 493–503. <https://doi.org/10.1037/0003-066x.54.7.493>
- Gollwitzer, P. M. (2014). Weakness of the will: Is a quick fix possible? *Motivation and Emotion*, 38, 305–322. <https://doi.org/10.1007/s11031-014-9416-3>
- Golosheykin, S., Grant, J. D., Novak, O. V., Heath, A. C., & Anokhin, A. P. (2017). Genetic influences on heart rate variability. *International Journal of Psychophysiology*, 115, 65–73. <https://doi.org/10.1016/j.ijpsycho.2016.04.008>
- Gough, H. G. (1987). *California Psychological Inventory—administrator’s guide*. Palo Alto, CA: Consulting Psychologists Press.
- Grasmick, H. G., Tittle, C. R., Bursik, R. J. J., & Arneklev, B. J. (1993). Testing the core empirical implications of Gottfredson and Hirschi’s general theory of crime. *Journal of Research in Crime and Delinquency*, 30, 5–29. <https://doi.org/10.1177/0022427893030001002>
- Gratton, G., Coles, M. G., & Donchin, E. (1992). Optimizing the use of information: Strategic control of activation of responses. *Journal of Experimental Psychology: General*, 121, 480–506. <https://doi.org/10.1037//0096-3445.121.4.480>
- Gross, J. J. (2015). Emotion regulation: Current status and future prospects. *Psychological Inquiry*, 26, 1–26. <https://doi.org/10.1080/1047840x.2014.940781>

## GENERAL INTRODUCTION

- Gröpel, P., Baumeister, R. F., & Beckmann, J. (2014). Action versus state orientation and self-control performance after depletion. *Personality and Social Psychology Bulletin, 40*, 476–487. <https://doi.org/10.1177/0146167213516636>
- Gustavson, D. E., Panizzon, M. S., Elman, J. A., Franz, C. E., Reynolds, C. A., Jacobson, K. C., Friedman, N. P., Xian, H., Toomey, R., Lyons, M. J., & Kremen, W. S. (2018). Stability of genetic and environmental influences on executive functions in midlife. *Psychology and Aging, 33*, 219–231. <https://doi.org/10.1037/pag0000230>
- Guy, S.C., Isquith, P.K., & Gioia, G.A. (2005). *Behavior rating inventory of executive function—self report version*. Odessa, Florida: Psychological Assessment Resources.
- Hagger, M. S., Wood, C., Stiff, C., & Chatzisarantis, N. L. D. (2010). Ego depletion and the strength model of self-control: A meta-analysis. *Psychological Bulletin, 136*, 495–525. <https://doi.org/10.1037/a0019486>
- Hagger, M. S., Chatzisarantis, N. L. D., Alberts, H., Anggono, C. O., Batailler, C., Birt, A. R., Brand, R., Brandt, M. J., Brewer, G., Bruyneel, S., Calvillo, D. P., Campbell, W. K., Cannon, P. R., Carlucci, M., Carruth, N. P., Cheung, T., Crowell, A., de Ridder, D. T. D., Dewitte, S., ... Zwieneberg, M. (2016). A multilab preregistered replication of the ego-depletion effect. *Perspectives on Psychological Science, 11*, 546–573. <https://doi.org/10.1177/1745691616652873>
- Hainsworth, R. (1995). The control and physiological importance of heart rate. In M. Malik & A. J. Camm (Eds.), *Heart rate variability* (pp. 3–19). Armonk, NY: Futura Pub. Co. Inc.
- Haslacher, H., Michlmayr, M., Batmyagmar, D., Perkmann, T., Ponocny-Seliger, E., Scheichenberger, V., Winker, R. (2015). Physical exercise counteracts genetic susceptibility to depression. *Neuropsychobiology, 71*, 168–175. <https://doi.org/10.1159/000381350>

## GENERAL INTRODUCTION

- Heatherston, T. F., & Wagner, D. D. (2011). Cognitive neuroscience of self-regulation failure. *Trends in Cognitive Sciences*, *15*, 132–139. <https://doi.org/10.1016/j.tics.2010.12.005>
- Hedge, C., Powell, G., & Sumner, P. (2018). The reliability paradox: Why robust cognitive tasks do not produce reliable individual differences. *Behavior Research Methods*, *50*, 1166–1186. <https://doi.org/10.3758/s13428-017-0935-1>
- Heijnen, S., Hommel, B., Kibele, A., & Colzato, L. S. (2016). Neuromodulation of aerobic exercise—a review. *Frontiers in Psychology*, *6*. <https://doi.org/10.3389/fpsyg.2015.01890>
- Henje Blom, E., Olsson, E. M. G., Serlachius, E., Ericson, M., & Ingvar, M. (2009). Heart rate variability is related to self-reported physical activity in a healthy adolescent population. *European Journal of Applied Physiology*, *106*, 877–883. <https://doi.org/10.1007/s00421-009-1089-3>
- Hillmann, C. H., Castelli, D. M., & Buck, S. M. (2005). Aerobic fitness and neurocognitive function in healthy preadolescent children. *Medicine & Science in Sports & Exercise*, *37*, 1967–1974. <https://doi.org/10.1249/01.mss.0000176680.79702.ce>
- Hillman, C. H., Erickson, K. I., & Kramer, A. F. (2008). Be smart, exercise your heart: Exercise effects on brain and cognition. *Nature Reviews Neuroscience*, *9*, 58–65. <https://doi.org/10.1038/nrn2298>
- Hillman, C. H., McAuley, E., Erickson, K. I., Liu-Ambrose, T., & Kramer, A. F. (2018). On mindful and mindless physical activity and executive function: A response to Diamond and Ling (2016). *Developmental Cognitive Neuroscience*. <https://doi.org/10.1016/j.dcn.2018.01.006>
- Hofmann, W., Baumeister, R. F., Förster, G., & Vohs, K. D. (2012). Everyday temptations: An experience sampling study of desire, conflict, and self-control. *Journal of Personality and Social Psychology*, *102*, 1318–1335. <https://doi.org/10.1037/a0026545>

- Hofmann, W., Gschwendner, T., Friese, M., Wiers, R. W., & Schmitt, M. (2008). Working memory capacity and self-regulatory behavior: Toward an individual differences perspective on behavior determination by automatic versus controlled processes. *Journal of Personality and Social Psychology, 95*, 962–977. <https://doi.org/10.1037/a0012705>
- Hofmann, W., Rauch, W., & Gawronski, B. (2007). And deplete us not into temptation: Automatic attitudes, dietary restraint, and self-regulatory resources as determinants of eating behavior. *Journal of Experimental Social Psychology, 43*, 497–504. <https://doi.org/10.1016/j.jesp.2006.05.004>
- Hofmann, W., Schmeichel, B. J., & Baddeley, A. D. (2012). Executive functions and self-regulation. *Trends in Cognitive Sciences, 16*, 174–180. <https://doi.org/10.1016/j.tics.2012.01.006>
- Hofmann, W., & Van Dillen, L. (2012). Desire: The new hot spot in self-control research. *Current Directions in Psychological Science, 21*, 317–322. <https://doi.org/10.1177/0963721412453587>
- Hofmann, W. & Vohs, K. D. (2016). Desire and self-regulation. In K. D. Vohs & R. F. Baumeister (Eds.), *Handbook of self-regulation: Research, theory and applications* (3rd ed., pp. 76–94). New York, NY: Guilford Press.
- Holzman, J. B., & Bridgett, D. J. (2017). Heart rate variability indices as bio-markers of top-down self-regulatory mechanisms: A meta-analytic review. *Neuroscience & Biobehavioral Reviews, 74*, 233–255. <https://doi.org/10.1016/j.neubiorev.2016.12.032>
- Hoyle, R. H., & Davisson, E. K. (2016). Varieties of self-control and their personality correlates. In K. D. Vohs & R. F. Baumeister (Eds.), *Handbook of self-regulation: Research, theory and applications* (3rd ed., pp. 396–413). New York, NY: Guilford Press.
- Imhoff, R., Schmidt, A. F., & Gerstenberg, F. (2014). Exploring the interplay of trait self-

## GENERAL INTRODUCTION

- control and ego depletion: Empirical evidence for ironic effects. *European Journal of Personality*, 28, 413–424. <https://doi.org/10.1002/per.1899>
- Inzlicht, M., & Schmeichel, B. J. (2012). What is ego depletion? Toward a mechanistic revision of the resource model of self-control. *Perspectives on Psychological Science*, 7, 450–463. <https://doi.org/10.1177/1745691612454134>
- Inzlicht, M., Schmeichel, B. J., & Macrae, C. N. (2014). Why self-control seems (but may not be) limited. *Trends in Cognitive Sciences*, 18, 127–133. <https://doi.org/10.1016/j.tics.2013.12.009>
- Jacobson, E. (1938). *Progressive relaxation*. Chicago: University of Chicago press.
- Job, V., Walton, G. M., Bernecker, K., & Dweck, C. S. (2013). Beliefs about willpower determine the impact of glucose on self-control. *Proceedings of the National Academy of Sciences*, 110, 14837–14842. <https://doi.org/10.1073/pnas.1313475110>
- Jostmann, N. B., & Koole, S. L. (2007). On the regulation of cognitive control: Action orientation moderates the impact of high demands in Stroop interference tasks. *Journal of Experimental Psychology: General*, 136, 593–609. <https://doi.org/10.1037/0096-3445.136.4.593>
- Jostmann, N. B., & Koole, S. L. (2009). When persistence is futile: A functional analysis of action orientation and goal disengagement. In G.B. Moskowitz & H. Grant (Eds.), *The psychology of goals* (pp. 337–361). New York, NY: Guilford Press.
- Kable, J. W. (2014). Valuation, intertemporal choice, and self-control. In P. W. Glimcher & E. Fehr (Eds.), *Neuroeconomics. Decision making and the brain* (2nd ed., pp. 173–192). London: Academic Press.
- Kane, M. J., Bleckley, M. K., Conway, A. R. A., & Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General*, 130,

## GENERAL INTRODUCTION

169–183. <https://doi.org/10.1037/0096-3445.130.2.169>

Kane, M. J., & Engle, R. W. (2002). The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: An individual-differences perspective.

*Psychonomic Bulletin & Review*, 9, 637–671. <https://doi.org/10.3758/bf03196323>

Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention:

The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General*, 132, 47–70.

<https://doi.org/10.1037/0096-3445.132.1.47>

Kanfer, R., Dugdale, B., & McDonald, B. (1994). Empirical findings on the Action Control

Scale in the context of complex skill acquisition. In J. Kuhl, & J. Beckmann (Eds.),

*Volition and personality: Action versus state orientation* (pp. 61–77). Göttingen,

Germany: Hogrefe & Huber Publishers.

Kaplan, S., & Berman, M. G. (2010). Directed attention as a common resource for executive

functioning and self-regulation. *Perspectives on Psychological Science*, 5, 43–57.

<https://doi.org/10.1177/1745691609356784>

Karason, K., Mølgaard, H., Wikstrand, J., & Sjöström, L. (1999). Heart rate variability in

obesity and the effect of weight loss. *The American Journal of Cardiology*, 83, 1242–1247.

[https://doi.org/10.1016/s0002-9149\(99\)00066-1](https://doi.org/10.1016/s0002-9149(99)00066-1)

Karavidas, M. K., Lehrer, P. M., Vaschillo, E., Vaschillo, B., Marin, H., Buyske, S.,

Malinovsky, I., Radvanski, D., & Hasset, A. (2007). Preliminary results of an open label

study of heart rate variability biofeedback for the treatment of major depression. *Applied*

*Psychophysiology and Biofeedback*, 32, 19–30. <https://doi.org/10.1007/s10484-006-9029->

z

Karr, J. E., Areshenkoff, C. N., Rast, P., Hofer, S. M., Iverson, G. L., & Garcia-Barrera, M. A.

## GENERAL INTRODUCTION

- (2018). The unity and diversity of executive functions: A systematic review and re-analysis of latent variable studies. *Psychological Bulletin*, *144*, 1147–1185. <https://doi.org/10.1037/bul0000160>
- Kaschel, R., & Kuhl, J. (2004). Motivational counseling in an extended functional context: Personality systems interaction theory and assessment. In W.M. Cox & E. Klinger (Eds.), *Handbook of motivational counseling: Motivating people for change* (pp. 99–119). Sussex: Wiley.
- Kassai, R., Futo, J., Demetrovics, Z., & Takacs, Z. K. (2019). A meta-analysis of the experimental evidence on the near- and far-transfer effects among children's executive function skills. *Psychological Bulletin*, *145*, 165–188. <https://doi.org/10.1037/bul0000180>
- Kazén, M., & Quirin, M. (2018). The integration of motivation and volition in Personality Systems Interactions (PSI) theory. In N. Baumann, M. Kazén, M. Quirin, & S. L. Koole (Eds.), *Why people do the things they do: Building on Julius Kuhl's contributions to the psychology of motivation and volition* (pp. 15–30). Göttingen, Germany: Hogrefe.
- Kämpfe, N., & Mitte, K. (2009). A German validation of the UPPS Impulsive Behavior Scale. *European Journal of Psychological Assessment*, *25*, 252–259. <https://doi.org/10.1027/1015-5759.25.4.252>
- Kelley, T. L. (1927). *Interpretation of educational measurements* (pp. 62–65). Yonkers-on-Hudson, New York, NY: World Book Company.
- Kelley, N. J., Finley, A. J., & Schmeichel, B. J. (2019). After-effects of self-control: The reward responsivity hypothesis. *Cognitive, Affective, & Behavioral Neuroscience*, *19*, 600–618. <https://doi.org/10.3758/s13415-019-00694-3>
- Kendall, P. C., & Williams, C. L. (1982). Assessing the cognitive and behavioral components of children's self-management. In P. Karoly & F. H. Kanfer (Eds.), *Self-management and*

## GENERAL INTRODUCTION

*behavior change* (pp. 240–284). New York, NY: Pergamon.

- Keye, D., Wilhelm, O., & Oberauer, K. (2009). Structure and correlates of the German version of the brief UPPS Impulsive Behavior Scales. *European Journal of Psychological Assessment, 25*, 175–185. <https://doi.org/10.1027/1015-5759.25.3.175>
- Kidd, C., Palmeri, H., & Aslin, R. N. (2013). Rational snacking: Young children's decision-making on the marshmallow task is moderated by beliefs about environmental reliability. *Cognition, 126*, 109–114. <https://doi.org/10.1016/j.cognition.2012.08.004>
- Koenig, J., & Thayer, J. F. (2016). Sex differences in healthy human heart rate variability: A meta-analysis. *Neuroscience & Biobehavioral Reviews, 64*, 288–310. <https://doi.org/10.1016/j.neubiorev.2016.03.007>
- Kok, B. E., Coffey, K. A., Cohn, M. A., Catalino, L. I., Vacharkulksemsuk, T., Algoe, S. B., Brantley, M., & Fredrickson, B. L. (2013). How positive emotions build physical health: Perceived positive social connections account for the upward spiral between positive emotions and vagal tone. *Psychological Science, 24*, 1123–1132. <https://doi.org/10.1177/0956797612470827>
- Kok, B. E., & Fredrickson, B. L. (2010). Upward spirals of the heart: Autonomic flexibility, as indexed by vagal tone, reciprocally and prospectively predicts positive emotions and social connectedness. *Biological Psychology, 85*, 432–436. <https://doi.org/10.1016/j.biopsycho.2010.09.005>
- Koole, S. L., & Fockenberg, D. A. (2011). Implicit emotion regulation under demanding conditions: The moderating role of action versus state orientation. *Cognition & Emotion, 25*, 440–452. <https://doi.org/10.1080/02699931.2010.544891>
- Koole, S. L., & Jostmann, N. B. (2004). Getting a grip on your feelings: Effects of action orientation and external demands on intuitive affect regulation. *Journal of Personality and*

## GENERAL INTRODUCTION

*Social Psychology*, 87, 974–990. <https://doi.org/10.1037/0022-3514.87.6.974>

Koole, S. L., Jostmann, N. B., & Baumann, N. (2012). Do demanding conditions help or hurt self-regulation? *Social and Personality Psychology Compass*, 6, 328–346. <https://doi.org/10.1111/j.1751-9004.2012.00425.x>

Koole, S. L., Kuhl, J., Jostmann, N. B., & Vohs, K. D. (2005). On the hidden benefits of state orientation: Can people prosper without efficient affect regulation skills? In A. Tesser, J. Wood, & D. A. Stapel (Eds.), *On building, defending, and regulating the self: A psychological perspective* (pp. 217–243). London, UK: Taylor & Francis.

Koole, S. L., Smeets, K., van Knippenberg, A., & Dijksterhuis, A. (1999). The cessation of rumination through self-affirmation. *Journal of Personality and Social Psychology*, 77, 111–125. <https://doi.org/10.1037/0022-3514.77.1.111>

Kotabe, H. P., & Hofmann, W. (2015). On integrating the components of self-control. *Perspectives on Psychological Science*, 10, 618–638. <https://doi.org/10.1177/1745691615593382>

Krönke, K.-M., Wolff, M., Mohr, H., Kräplin, A., Smolka, M. N., Bühringer, G., & Goschke, T. (2020). Predicting real-life self-control from brain activity encoding the value of anticipated future outcomes. *Psychological Science*, 31, 268–279. [doi:10.1177/0956797619896357](https://doi.org/10.1177/0956797619896357)

Kruglanski, A. W., & Gigerenzer, G. (2011). Intuitive and deliberate judgments are based on common principles. *Psychological Review*, 118, 97–109. <https://doi.org/10.1037/a0020762>

Kuhl, J. (1990). *Der Fragebogen zur Erfassung von Handlungs- versus Lageorientierung (HAKEMP-90) [The questionnaire for assessing action versus state orientation (ACS-90)]*. Unpublished manuscript, University of Osnabrück, Germany.

## GENERAL INTRODUCTION

- Kuhl, J. (1994a). A theory of action and state orientations. In J. Kuhl & J. Beckmann (Eds.), *Volition and personality: Action versus state orientation* (pp. 9–46). Göttingen, Germany: Hogrefe & Huber Publishers.
- Kuhl, J. (1994b). Action versus state orientation: Psychometric properties of the Action Control Scale (ACS-90). In J. Kuhl & J. Beckmann (Eds.), *Volition and personality: Action versus state orientation* (pp. 47–59). Göttingen, Germany: Hogrefe & Huber Publishers.
- Kuhl, J. (2000). A functional-design approach to motivation and self-regulation: The dynamics of personality systems interactions. In M. Boekaerts, P. R. Pintrich, & M. Zeidner (Eds.), *Handbook of self-regulation* (pp. 111–169). Burlington, MA: Elsevier/Academic Press.  
<https://doi.org/10.1016/B978-012109890-2/50034-2>
- Kuhl, J. (2018). Individual differences in self-regulation. In J. Heckhausen, H. Heckhausen (Eds.), *Motivation and action* (pp. 529–577). Springer, Cham.  
[https://doi.org/10.1007/978-3-319-65094-4\\_13](https://doi.org/10.1007/978-3-319-65094-4_13)
- Kurzban, R. (2010). Does the brain consume additional glucose during self-control tasks? *Evolutionary Psychology*, 8, 244–259. <https://doi.org/10.1177/147470491000800208>
- Kurzban, R., Duckworth, A., Kable, J. W., & Myers, J. (2013). An opportunity cost model of subjective effort and task performance. *Behavioral and Brain Sciences*, 36, 661–679.  
<https://doi.org/10.1017/s0140525x12003196>
- Kusche, C. A., & Greenberg, M. T. (1994). *The PATHS curriculum*. Seattle, WA: Developmental Research and Programs.
- Laborde, S., Mosley, E., & Mertgen, A. (2018a). A unifying conceptual framework of factors associated to cardiac vagal control. *Heliyon*, 4, e01002.  
<https://doi.org/10.1016/j.heliyon.2018.e01002>
- Laborde, S., Mosley, E., & Mertgen, A. (2018b). Vagal tank theory: The three Rs of cardiac

## GENERAL INTRODUCTION

- vagal control functioning—resting, reactivity, and recovery. *Frontiers in Neuroscience*, *12*.  
<https://doi.org/10.3389/fnins.2018.00458>
- Laborde, S., Mosley, E., & Thayer, J. F. (2017). Heart rate variability and cardiac vagal tone in psychophysiological research—recommendations for experiment planning, data analysis, and data reporting. *Frontiers in Psychology*, *8*. <https://doi.org/10.3389/fpsyg.2017.00213>
- Lange, F., & Eggert, F. (2014). Sweet delusion. Glucose drinks fail to counteract ego depletion. *Appetite*, *75*, 54–63. <https://doi.org/10.1016/j.appet.2013.12.020>
- Lee, K., Bull, R., & Ho, R. M. H. (2013). Developmental changes in executive functioning. *Child Development*, *84*, 1933–1953. <https://doi.org/10.1111/cdev.12096>
- Lehrer, P. (2013). How does heart rate variability biofeedback work? Resonance, the baroreflex, and other mechanisms. *Biofeedback*, *41*, 26–31. <https://doi.org/10.5298/1081-5937-41.1.02>
- Lehrer, P. M., & Gevirtz, R. (2014). Heart rate variability biofeedback: How and why does it work? *Frontiers in Psychology*, *5*. <https://doi.org/10.3389/fpsyg.2014.00756>
- Lehrer, P., Kaur, K., Sharma, A., Shah, K., Huseby, R., Bhavsar, J., & Zhang, Y. (2020). Heart rate variability biofeedback improves emotional and physical health and performance: A systematic review and meta analysis. *Applied Psychophysiology and Biofeedback*, *45*, 109–129. <https://doi.org/10.1007/s10484-020-09466-z>
- Lehrer, P. M., Vaschillo, E., & Vaschillo, B. (2000). Resonant frequency biofeedback training to increase cardiac variability: Rationale and manual for training. *Applied Psychophysiology and Biofeedback*, *25*, 177–191. <https://doi.org/10.1023/A:1009554825745>
- Lehrer, P. M., Vaschillo, E., Vaschillo, B., Lu, S.-E., Eckberg, D. L., Edelberg, R., Shih, W. J.; Lin, Y.; Kuusela, T. A.; Tahvanainen, K. U. O., & Hamer, R. M. (2003). Heart rate

## GENERAL INTRODUCTION

- variability biofeedback increases baroreflex gain and peak expiratory flow. *Psychosomatic Medicine*, *65*, 796–805. <https://doi.org/10.1097/01.psy.0000089200.81962.19>
- Lehrer, P. M., Vaschillo, E., Vaschillo, B., Lu, S.-E., Scardella, A., Siddique, M., & Habib, R. H. (2004). Biofeedback treatment for asthma. *Chest*, *126*, 352–361. <https://doi.org/10.1378/chest.126.2.352>
- Letzring, T. D., Block, J., & Funder, D. C. (2005). Ego-control and ego-resiliency: Generalization of self-report scales based on personality descriptions from acquaintances, clinicians, and the self. *Journal of Research in Personality*, *39*, 395–422. <https://doi.org/10.1016/j.jrp.2004.06.003>
- Lilienfeld, S. O., Wood, J. M., & Garb, H. N. (2000). The scientific status of projective techniques. *Psychological Science in the Public Interest*, *1*, 27–66. <https://doi.org/10.1111/1529-1006.002>
- Lin, I.-M. (2018). Effects of a cardiorespiratory synchronization training mobile application on heart rate variability and electroencephalography in healthy adults. *International Journal of Psychophysiology*, *134*, 168–177. <https://doi.org/10.1016/j.ijpsycho.2018.09.005>
- Lin, I.-M., Tai, L. Y., & Fan, S. Y. (2014). Breathing at a rate of 5.5 breaths per minute with equal inhalation-to-exhalation ratio increases heart rate variability. *International Journal of Psychophysiology*, *91*, 206–211. <https://doi.org/10.1016/j.ijpsycho.2013.12.006>
- Liston, C., McEwen, B. S., & Casey, B. J. (2009). Psychosocial stress reversibly disrupts prefrontal processing and attentional control. *Proceedings of the National Academy of Sciences*, *106*, 912–917. <https://doi.org/10.1073/pnas.0807041106>
- Lu, C. L., Zou, X., Orr, W. C., and Chen, J. D. (1999). Postprandial changes of sympathovagal balance measured by heart rate variability. *Digestive Diseases and Sciences*, *44*, 857–861.
- Lü, W., Wang, Z., & Liu, Y. (2013). A pilot study on changes of cardiac vagal tone in

- individuals with low trait positive affect: The effect of positive psychotherapy. *International Journal of Psychophysiology*, 88, 213–217. <https://doi.org/10.1016/j.ijpsycho.2013.04.012>
- Lynam, D. R., Smith, G. T., Cyders, M. A., Fischer, S., & Whiteside, S. P. (2007). *The UPPS-P questionnaire measure of five dispositions to rash action* [Unpublished technical report]. Purdue University, West Lafayette, IN.
- Ma, F., Chen, B., Xu, F., Lee, K., & Heyman, G. D. (2018). Generalized trust predicts young children’s willingness to delay gratification. *Journal of Experimental Child Psychology*, 169, 118–125. <https://doi.org/10.1016/j.jecp.2017.12.015>
- Malanchini, M., Engelhardt, L. E., Grotzinger, A. D., Harden, K. P., & Tucker-Drob, E. M. (2019). “Same but different”: Associations between multiple aspects of self-regulation, cognition, and academic abilities. *Journal of Personality and Social Psychology*, 117, 1164–1188. <https://doi.org/10.1037/pspp0000224>
- Melby-Lervåg, M., & Hulme, C. (2013). Is working memory training effective? A meta-analytic review. *Developmental Psychology*, 49, 270–291. <https://doi.org/10.1037/a0028228>
- Meule, A., Vögele, C., & Kübler, A. (2011). Psychometrische Evaluation der deutschen Barratt Impulsiveness Scale–Kurzversion (BIS-15) [Psychometric evaluation of the German Barratt Impulsiveness Scale–short version (BIS-15)]. *Diagnostica*, 57, 126–133. <https://doi.org/10.1026/0012-1924/a000042>
- Mischel, W., Ayduk, O., Berman, M. G., Casey, B. J., Gotlib, I. H., Jonides, J., Kross, E., Teslovich, T., Wilson, N. L., Zayas, V., & Shoda, Y. (2011). ‘Willpower’ over the life span: Decomposing self-regulation. *Social Cognitive and Affective Neuroscience*, 6, 252–256. <https://doi.org/10.1093/scan/nsq081>

## GENERAL INTRODUCTION

- Mischel, W., Ebbesen, E. B., & Raskoff Zeiss, A. (1972). Cognitive and attentional mechanisms in delay of gratification. *Journal of Personality and Social Psychology*, *21*, 204–218. <https://doi.org/10.1037/h0032198>
- Mischel, W., Shoda, Y., & Peake, P. K. (1988). The nature of adolescent competencies predicted by preschool delay of gratification. *Journal of Personality and Social Psychology*, *54*, 687–696. <https://doi.org/10.1037/0022-3514.54.4.687>
- Milyavskaya, M., Berkman, E. T., & de Ridder, D. T. D. (2019). The many faces of self-control: Tacit assumptions and recommendations to deal with them. *Motivation Science*, *5*, 79–85. <https://doi.org/10.1037/mot0000108>
- Milyavskaya, M., & Inzlicht, M. (2017). What’s so great about self-control? Examining the importance of effortful self-control and temptation in predicting real-life depletion and goal attainment. *Social Psychological and Personality Science*, *8*, 603–611. <https://doi.org/10.1177/1948550616679237>
- Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions. *Current Directions in Psychological Science*, *21*, 8–14. <https://doi.org/10.1177/0963721411429458>
- Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cognitive Psychology*, *41*, 49–100. <https://doi.org/10.1006/cogp.1999.0734>
- Moffitt, T. E., Arseneault, L., Belsky, D., Dickson, N., Hancox, R. J., Harrington, H., Houts, R., Poulton, R., Roberts, B. W., Ross, S., Sears, M. R., Thomson, W. M., & Caspi, A. (2011). A gradient of childhood self-control predicts health, wealth, and public safety. *Proceedings of the National Academy of Sciences*, *108*, 2693–2698.

## GENERAL INTRODUCTION

<https://doi.org/10.1073/pnas.1010076108>

- Molden, D. C., Hui, C. M., Scholer, A. A., Meier, B. P., Noreen, E. E., D'Agostino, P. R., & Martin, V. (2012). Motivational versus metabolic effects of carbohydrates on self-control. *Psychological Science, 23*, 1137–1144. <https://doi.org/10.1177/0956797612439069>
- Moller, A. C., Deci, E. L., & Ryan, R. M. (2006). Choice and ego-depletion: The moderating role of autonomy. *Personality and Social Psychology Bulletin, 32*, 1024–1036. <https://doi.org/10.1177/0146167206288008>
- Moreau, D., & Conway, A. R. A. (2014). The case for an ecological approach to cognitive training. *Trends in Cognitive Sciences, 18*, 334–336. <https://doi.org/10.1016/j.tics.2014.03.009>
- Muraven, M., Collins, R. L., & Neinhuis, K. (2002). Self-control and alcohol restraint: An initial application of the self-control strength model. *Psychology of Addictive Behaviors, 16*, 113–120. <https://doi.org/10.1037/0893-164x.16.2.113>
- Muraven, M., Gagné, M., & Rosman, H. (2008). Helpful self-control: Autonomy support, vitality, and depletion. *Journal of Experimental Social Psychology, 44*, 573–585. <https://doi.org/10.1016/j.jesp.2007.10.008>
- Muraven, M., Shmueli, D., & Burkley, E. (2006). Conserving self-control strength. *Journal of Personality and Social Psychology, 91*, 524–537. <https://doi.org/10.1037/0022-3514.91.3.524>
- Muraven, M., & Slessareva, E. (2003). Mechanisms of self-control failure: Motivation and limited resources. *Personality and Social Psychology Bulletin, 29*, 894–906. <https://doi.org/10.1177/0146167203029007008>
- Muraven, M., Tice, D. M., & Baumeister, R. F. (1998). Self-control as a limited resource: Regulatory depletion patterns. *Journal of Personality and Social Psychology, 74*, 774–

## GENERAL INTRODUCTION

789. <https://doi.org/10.1037/0022-3514.74.3.774>

Neys, W. D. (2006). Dual processing in reasoning. *Psychological Science, 17*, 428–433.

<https://doi.org/10.1111/j.1467-9280.2006.01723.x>

Nigg, J. T. (2017). Annual research review: On the relations among self-regulation, self-control, executive functioning, effortful control, cognitive control, impulsivity, risk-taking, and inhibition for developmental psychopathology. *Journal of Child Psychology and Psychiatry, 58*, 361–383. <https://doi.org/10.1111/jcpp.12675>

Nunan, D., Sandercock, G. R. H., & Brodie, D. A. (2010). A quantitative systematic review of normal values for short-term heart rate variability in healthy adults. *Pacing and Clinical Electrophysiology, 33*, 1407–1417. <https://doi.org/10.1111/j.1540-8159.2010.02841.x>

Oveis, C., Cohen, A. B., Gruber, J., Shiota, M. N., Haidt, J., & Keltner, D. (2009). Resting respiratory sinus arrhythmia is associated with tonic positive emotionality. *Emotion, 9*, 265–270. <https://doi.org/10.1037/a0015383>

Painelli, V. de S., Nicastro, H., & Lancha, A. H. (2010). Carbohydrate mouth rinse: Does it improve endurance exercise performance? *Nutrition Journal, 9*. <https://doi.org/10.1186/1475-2891-9-33>

Patton, J. H., Stanford, M. S., & Barratt, E. S. (1995). Factor structure of the Barratt Impulsiveness Scale. *Journal of Clinical Psychology, 51*, 768–774. [https://doi.org/10.1002/1097-4679\(199511\)51:6<768::AID-JCLP2270510607>3.0.CO;2-1](https://doi.org/10.1002/1097-4679(199511)51:6<768::AID-JCLP2270510607>3.0.CO;2-1)

Porges, S. W. (2001). The polyvagal theory: Phylogenetic substrates of a social nervous system. *International Journal of Psychophysiology, 42*, 123–146. [https://doi.org/10.1016/s0167-8760\(01\)00162-3](https://doi.org/10.1016/s0167-8760(01)00162-3)

Porges, S. W. (2007). The polyvagal perspective. *Biological Psychology, 74*, 116–143.

## GENERAL INTRODUCTION

<https://doi.org/10.1016/j.biopsycho.2006.06.009>

Powell, D. J. H., McMinn, D., & Allan, J. L. (2017). Does real time variability in inhibitory control drive snacking behavior? An intensive longitudinal study. *Health Psychology, 36*, 356–364. <https://doi.org/10.1037/hea0000471>

Quintana, D. S., & Heathers, J. A. J. (2014). Considerations in the assessment of heart rate variability in biobehavioral research. *Frontiers in Psychology, 5*. <https://doi.org/10.3389/fpsyg.2014.00805>

Redick, T. S., & Lindsey, D. R. B. (2013). Complex span and n-back measures of working memory: A meta-analysis. *Psychonomic Bulletin & Review, 20*, 1102–1113. <https://doi.org/10.3758/s13423-013-0453-9>

Rethorst, C. D., Wipfli, B. M., & Landers, D. M. (2009). The antidepressive effects of exercise. *Sports Medicine, 39*, 491–511. <https://doi.org/10.2165/00007256-200939060-00004>

Robson, D. A., Allen, M. S., & Howard, S. J. (2020). Self-regulation in childhood as a predictor of future outcomes: A meta-analytic review. *Psychological Bulletin, 146*, 324–354. <https://doi.org/10.1037/bul0000227>

Rosenbaum, M. (1980). A schedule for assessing self-control behaviors: Preliminary findings. *Behavior Therapy, 11*, 109–121. [https://doi.org/10.1016/s0005-7894\(80\)80040-2](https://doi.org/10.1016/s0005-7894(80)80040-2)

Roth, R.M., Isquith, P.K., & Gioia, G.A. (2005). *Behavior rating inventory of executive function—adult version*. Lutz, Florida: Psychological Assessment Resources.

Ruigendijk, H. A. H., Jostmann, N. B., & Koole, S. L. (2018). Why the road to hell is paved with good intentions: Paradoxical effects of volitional action control. In N. Baumann, M. Kazén, M. Quirin, & S. L. Koole (Eds.), *Why people do the things they do: Building on Julius Kuhl's contributions to the psychology of motivation and volition* (pp. 151–165). Göttingen, Germany: Hogrefe.

## GENERAL INTRODUCTION

- Ruigendijk, H. A. H., & Koole, S. L. (2014). When focusing on a goal interferes with action control: Action versus state orientation and over-maintenance of intentions. *Motivation and Emotion, 38*, 659–672. <https://doi.org/10.1007/s11031-014-9415-4>
- Saunders, B., Milyavskaya, M., Etz, A., Randles, D., & Inzlicht, M. (2018). Reported self-control is not meaningfully associated with inhibition-related executive function: A Bayesian analysis. *Collabra: Psychology, 4*. <https://doi.org/10.1525/collabra.134>
- Savani, K., & Job, V. (2017). Reverse ego-depletion: Acts of self-control can improve subsequent performance in Indian cultural contexts. *Journal of Personality and Social Psychology, 113*, 589–607. <https://doi.org/10.1037/pspi0000099>
- Schimmack, U. (2012). The ironic effect of significant results on the credibility of multiple-study articles. *Psychological Methods, 17*, 551–566. <https://doi.org/10.1037/a0029487>
- Schmeichel, B. J., & Tang, D. (2015). Individual differences in executive functioning and their relationship to emotional processes and responses. *Current Directions in Psychological Science, 24*, 93–98. <https://doi.org/10.1177/0963721414555178>
- Schmeichel, B. J., & Vohs, K. (2009). Self-affirmation and self-control: Affirming core values counteracts ego depletion. *Journal of Personality and Social Psychology, 96*, 770–782. <https://doi.org/10.1037/a0014635>
- Schmiedek, F., Lövdén, M., & Lindenberger, U. (2014). A task is a task is a task: Putting complex span, n-back, and other working memory indicators in psychometric context. *Frontiers in Psychology, 5*. <https://doi.org/10.3389/fpsyg.2014.01475>
- Schmidt, F. T. C., Fleckenstein, J., Retelsdorf, J., Eskreis-Winkler, L., & Möller, J. (2019). Measuring grit: A German validation and a domain-specific approach to grit. *European Journal of Psychological Assessment, 35*, 436–447. <https://doi.org/10.1027/1015-5759/a000407>

## GENERAL INTRODUCTION

- Schmidt, R. E., Gay, P., d'Acromont, M., & Van der Linden, M. (2008). A German adaptation of the UPPS Impulsive Behavior Scale: Psychometric properties and factor structure. *Swiss Journal of Psychology, 67*, 107–112. <https://doi.org/10.1024/1421-0185.67.2.107>
- Schoofs, D., Wolf, O. T., & Smeets, T. (2009). Cold pressor stress impairs performance on working memory tasks requiring executive functions in healthy young men. *Behavioral Neuroscience, 123*, 1066–1075. <https://doi.org/10.1037/a0016980>
- Schulte, D., Hartung, J., & Wilke, F. (1997). Handlungskontrolle der Angstbewältigung: Was macht Reizkonfrontationsverfahren so effektiv? [Action control in treatment of anxiety disorders: What makes exposure so effective?]. *Zeitschrift für Klinische Psychologie, 26*, 118–128.
- Schumann, A., Köhler, S., Brotte, L., & Bär, K.-J. (2019). Effect of an eight-week smartphone-guided HRV-biofeedback intervention on autonomic function and impulsivity in healthy controls. *Physiological Measurement, 40*, 064001. <https://doi.org/10.1088/1361-6579/ab2065>
- Schwerdtfeger, A. R., Rominger, C., & Obser, P. D. (2020). A shy heart may benefit from everyday life social interactions with close others: An ecological momentary assessment trial using Bayesian multilevel modeling. *Biological Psychology, 152*, 107864. <https://doi.org/10.1016/j.biopsycho.2020.107864>
- Schwerdtfeger, A. R., Schwarz, G., Pfurtscheller, K., Thayer, J. F., Jarczok, M. N., & Pfurtscheller, G. (2019). Heart rate variability (HRV): From brain death to resonance breathing at 6 breaths/minute. *Clinical Neurophysiology, 131*, 676–693. <https://doi.org/10.1016/j.clinph.2019.11.013>
- Scudder, M. R., Lambourne, K., Drollette, E. S., Herrmann, S. D., Washburn, R. A., Donnelly, J. E., & Hillman, C. H. (2014). Aerobic capacity and cognitive control in elementary

## GENERAL INTRODUCTION

school-age children. *Medicine & Science in Sports & Exercise*, 46, 1025–1035.

<https://doi.org/10.1249/mss.0000000000000199>

Seckendorff, R. v. (2009). *Auswirkungen eines 6-wöchigen Entspannungstrainings (Progressive Muskelrelaxation nach Jacobson) auf Blutdruck, Herzfrequenz und Herzratenvariabilität sowie psychologische Parameter (Stresserleben, Angst, Ärger) bei gesunden Probanden [Effects of a 6-week relaxation training (progressive muscle relaxation according to Jacobson) on blood pressure, heart rate and heart rate variability as well as psychological parameters (stress, anxiety, anger) in healthy individuals]*.

Doctoral dissertation Medizinischen Fakultät Charité Universitätsmedizin Berlin

Segerstrom, S. C., & Nes, L. S. (2007). Heart rate variability reflects self-regulatory strength, effort, and fatigue. *Psychological Science*, 18, 275–281. <https://doi.org/10.1111/j.1467-9280.2007.01888.x>

Shaffer, F., & Ginsberg, J. P. (2017). An overview of heart rate variability metrics and norms. *Frontiers in Public Health*, 5. <https://doi.org/10.3389/fpubh.2017.00258>

Shaffer, F., McCraty, R., & Zerr, C. L. (2014). A healthy heart is not a metronome: An integrative review of the heart's anatomy and heart rate variability. *Frontiers in Psychology*, 5. <https://doi.org/10.3389/fpsyg.2014.01040>

Sharma, L., Markon, K. E., & Clark, L. A. (2014). Toward a theory of distinct types of “impulsive” behaviors: A meta-analysis of self-report and behavioral measures. *Psychological Bulletin*, 140, 374–408. <https://doi.org/10.1037/a0034418>

Shields, G. S., Doty, D., Shields, R. H., Gower, G., Slavich, G. M., & Yonelinas, A. P. (2017). Recent life stress exposure is associated with poorer long-term memory, working memory, and self-reported memory. *Stress*, 20, 598–607. <https://doi.org/10.1080/10253890.2017.1380620>

## GENERAL INTRODUCTION

- Shoda, Y., Mischel, W., & Peake, P. K. (1990). Predicting adolescent cognitive and self-regulatory competencies from preschool delay of gratification: Identifying diagnostic conditions. *Developmental Psychology*, *26*, 978–986. <https://doi.org/10.1037/0012-1649.26.6.978>
- Sibley, B. A., & Etnier, J. L. (2003). The relationship between physical activity and cognition in children: A meta-analysis. *Pediatric Exercise Science*, *15*, 243–256. <https://doi.org/10.1123/pes.15.3.243>
- Siepmann, M., Aykac, V., Unterdörfer, J., Petrowski, K., & Mueck-Weymann, M. (2008). A pilot study on the effects of heart rate variability biofeedback in patients with depression and in healthy subjects. *Applied Psychophysiology and Biofeedback*, *33*, 195–201. <https://doi.org/10.1007/s10484-008-9064-z>
- Singer, J. L. (1955). Delayed gratification and ego development: Implications for clinical and experimental research. *Journal of Consulting Psychology*, *19*, 259–266. <https://doi.org/10.1037/h0044541>
- Singh, A. S., Saliassi, E., van den Berg, V., Uijtdewilligen, L., de Groot, R. H. M., Jolles, J., Andersen, L. B., Bailey, R., Chang, Y.-K., Diamond, A., Ericsson, I., Etnier, J. L., Fedewa, A. L., Hillman, C. H., McMorris, T., Pesce, C., Pühse, U., Tomporowski, P. D., Chinapaw, M. J. M. (2018). Effects of physical activity interventions on cognitive and academic performance in children and adolescents: A novel combination of a systematic review and recommendations from an expert panel. *British Journal of Sports Medicine*, 1–10. <https://doi.org/10.1136/bjsports-2017-098136>
- Sjoberg, N., & Saint, D. A. (2011). A single 4 mg dose of nicotine decreases heart rate variability in healthy nonsmokers: Implications for Smoking Cessation Programs. *Nicotine & Tobacco Research*, *13*, 369–372. <https://doi.org/10.1093/ntr/ntr004>

## GENERAL INTRODUCTION

- Sklerov, M., Dayan, E., & Browner, N. (2018). Functional neuroimaging of the central autonomic network: Recent developments and clinical implications. *Clinical Autonomic Research*. <https://doi.org/10.1007/s10286-018-0577-0>
- Smith, R., Thayer, J. F., Khalsa, S. S., & Lane, R. D. (2017). The hierarchical basis of neurovisceral integration. *Neuroscience & Biobehavioral Reviews*, *75*, 274–296. <https://doi.org/10.1016/j.neubiorev.2017.02.003>
- Soto, D., Hodsoll, J., Rotshtein, P., & Humphreys, G. W. (2008). Automatic guidance of attention from working memory. *Trends in Cognitive Sciences*, *12*, 342–348.
- Stahl, C., Voss, A., Schmitz, F., Nuszbaum, M., Tüscher, O., Lieb, K., & Klauer, K. C. (2014). Behavioral components of impulsivity. *Journal of Experimental Psychology: General*, *143*, 850–886. <https://doi.org/10.1037/a0033981>
- Stanley, J., Peake, J. M., & Buchheit, M. (2013). Cardiac parasympathetic reactivation following exercise: Implications for training prescription. *Sports Medicine*, *43*, 1259–1277. <https://doi.org/10.1007/s40279-013-0083-4>
- Sturge-Apple, M. L., Suor, J. H., Davies, P. T., Cicchetti, D., Skibo, M. A., & Rogosch, F. A. (2016). Vagal tone and children's delay of gratification: Differential sensitivity in resource-poor and resource-rich environments. *Psychological Science*, *27*, 885–893. <https://doi.org/10.1177/09567976166640269>
- Tan, G., Dao, T. K., Farmer, L., Sutherland, R. J., & Gevirtz, R. (2011). Heart rate variability (HRV) and posttraumatic stress disorder (PTSD): A pilot study. *Applied Psychophysiology and Biofeedback*, *36*, 27–35. <https://doi.org/10.1007/s10484-010-9141-y>
- Tangney, J. P., Baumeister, R. F., & Boone, A. L. (2004). High self-control predicts good adjustment, less pathology, better grades, and interpersonal success. *Journal of Personality*, *72*, 271–324. <https://doi.org/10.1111/j.0022-3506.2004.00263.x>

## GENERAL INTRODUCTION

- Tatschl, J. M., Hochfellner, S. M., & Schwerdtfeger, A. R. (2020). Implementing mobile HRV biofeedback as adjunctive therapy during inpatient psychiatric rehabilitation facilitates recovery of depressive symptoms and enhances autonomic functioning short-term: A 1-year pre–post-intervention follow-up pilot study. *Frontiers in Neuroscience, 14*, 738. <https://doi.org/10.3389/fnins.2020.00738>
- Thayer, J. F., Åhs, F., Fredrikson, M., Sollers, J. J., & Wager, T. D. (2012). A meta-analysis of heart rate variability and neuroimaging studies: Implications for heart rate variability as a marker of stress and health. *Neuroscience & Biobehavioral Reviews, 36*, 747–756. <https://doi.org/10.1016/j.neubiorev.2011.11.009>
- Thayer, J. F., Hansen, A. L., Saus-Rose, E., & Johnsen, B. H. (2009). Heart rate variability, prefrontal neural function, and cognitive performance: The neurovisceral integration perspective on self-regulation, adaptation, and health. *Annals of Behavioral Medicine, 37*, 141–153. <https://doi.org/10.1007/s12160-009-9101-z>
- Thayer, J. F., & Lane, R. D. (2000). A model of neurovisceral integration in emotion regulation and dysregulation. *Journal of Affective Disorders, 61*, 201–216. [https://doi.org/10.1016/s0165-0327\(00\)00338-4](https://doi.org/10.1016/s0165-0327(00)00338-4)
- Thayer, J. F., & Lane, R. D. (2009). Claude Bernard and the heart–brain connection: Further elaboration of a model of neurovisceral integration. *Neuroscience & Biobehavioral Reviews, 33*, 81–88. <https://doi.org/10.1016/j.neubiorev.2008.08.004>
- Thorndike, E. L. (1904). *An introduction to the theory of mental and social measurements*. New York, NY: Teachers College, Columbia University. <https://doi.org/10.1037/13283-000>
- Tice, D. M., Baumeister, R. F., Shmueli, D., & Muraven, M. (2007). Restoring the self: Positive affect helps improve self-regulation following ego depletion. *Journal of Experimental Social Psychology, 43*, 379–384. <https://doi.org/10.1016/j.jesp.2006.05.007>

## GENERAL INTRODUCTION

- Tice, D. M., Bratslavsky, E., & Baumeister, R. F. (2001). Emotional distress regulation takes precedence over impulse control: If you feel bad, do it!. *Journal of Personality and Social Psychology, 80*, 53–67. <https://doi.org/10.1037/0022-3514.80.1.53>
- Vadillo, M. A., Gold, N., & Osman, M. (2016). The bitter truth about sugar and willpower. *Psychological Science, 27*, 1207–1214. <https://doi.org/10.1177/0956797616654911>
- Van Eekelen, A. P. J., Houtveen, J. H., & Kerkhof, G. A. (2004). Circadian variation in cardiac autonomic activity: Reactivity measurements to different types of stressors. *Chronobiology International, 21*, 107–129. <https://doi.org/10.1081/cbi-120027983>
- Vaschillo, E. G., Vaschillo, B., & Lehrer, P. M. (2006). Characteristics of resonance in heart rate variability stimulated by biofeedback. *Applied Psychophysiology and Biofeedback, 31*, 129–142. <https://doi.org/10.1007/s10484-006-9009-3>
- Verguts, T., & Notebaert, W. (2008). Hebbian learning of cognitive control: Dealing with specific and nonspecific adaptation. *Psychological Review, 115*, 518–525. <https://doi.org/10.1037/0033-295x.115.2.518>
- Verguts, T., & Notebaert, W. (2009). Adaptation by binding: A learning account of cognitive control. *Trends in Cognitive Sciences, 13*, 252–257. <https://doi.org/10.1016/j.tics.2009.02.007>
- Vohs, K. D., Baumeister, R. F., & Schmeichel, B. J. (2012). Motivation, personal beliefs, and limited resources all contribute to self-control. *Journal of Experimental Social Psychology, 48*, 943–947. <https://doi.org/10.1016/j.jesp.2012.03.002>
- Vohs, K. D., & Heatherton, T. F. (2000). Self-regulatory failure: A resource-depletion approach. *Psychological Science, 11*, 249–254. <https://doi.org/10.1111/1467-9280.00250>
- Walk, L. M., Evers, W. F., Quante, S., & Hille, K. (2018). Evaluation of a teacher training program to enhance executive functions in preschool children. *PLOS ONE, 13*.

## GENERAL INTRODUCTION

<https://doi.org/10.1371/journal.pone.0197454>

Wang, Z., Lü, W., & Qin, R. (2013). Respiratory sinus arrhythmia is associated with trait positive affect and positive emotional expressivity. *Biological Psychology*, *93*, 190–196.

<https://doi.org/10.1016/j.biopsycho.2012.12.006>

Watts, T. W., Duncan, G. J., & Quan, H. (2018). Revisiting the marshmallow test: A conceptual replication investigating links between early delay of gratification and later outcomes.

*Psychological Science*, *29*, 1159–1177. <https://doi.org/10.1177/0956797618761661>

Webb, T. L., & Sheeran, P. (2003). Can implementation intentions help to overcome ego-depletion? *Journal of Experimental Social Psychology*, *39*, 279–286.

[https://doi.org/10.1016/s0022-1031\(02\)00527-9](https://doi.org/10.1016/s0022-1031(02)00527-9)

Wenzel, M., Rowland, Z., Zahn, D., & Kubiak, T. (2019). Let there be variance: Individual differences in consecutive self-control in a laboratory setting and daily life. *European Journal of Personality*, *33*, 468–487.

<https://doi.org/10.1002/per.2208>

Wetter, S. E., Fuhs, M., & Goodnight, J. A. (2019). Examining sleep as a protective mechanism for executive functioning in children from low-income homes. *Early Child Development and Care*, 1–12.

<https://doi.org/10.1080/03004430.2019.1573226>

Whiteside, S. P., & Lynam, D. R. (2001). The Five Factor Model and impulsivity: Using a structural model of personality to understand impulsivity. *Personality and Individual Differences*, *30*, 669–689.

[https://doi.org/10.1016/s0191-8869\(00\)00064-7](https://doi.org/10.1016/s0191-8869(00)00064-7)

Willems, Y. E., Boesen, N., Li, J., Finkenauer, C., & Bartels, M. (2019). The heritability of self-control: A meta-analysis. *Neuroscience & Biobehavioral Reviews*, *100*, 324–334.

<https://doi.org/10.1016/j.neubiorev.2019.02.012>

Willoughby, M. T., Blair, C. B., Wirth, R. J., & Greenberg, M. (2010). The measurement of executive function at age 3 years: Psychometric properties and criterion validity of a new

battery of tasks. *Psychological Assessment*, 22, 306-317.

- Wills, T. A., Vaccaro, D., and McNamara, G. (1994). Novelty seeking, risk taking, and related constructs as predictors of adolescent substance use: An application of Cloninger's theory. *Journal of Substance Abuse* 6, 1–20. [https://doi.org/10.1016/S0899-3289\(94\)90039-6](https://doi.org/10.1016/S0899-3289(94)90039-6)
- Wilfley, D. E., Hayes, J. F., Balantekin, K. N., Van Buren, D. J., & Epstein, L. H. (2018). Behavioral interventions for obesity in children and adults: Evidence base, novel approaches, and translation into practice. *American Psychologist*, 73, 981–993. <https://doi.org/10.1037/amp0000293>
- Wolff, M., Krönke, K.-M., Venz, J., Kräplin, A., Bühringer, G., Smolka, M. N., & Goschke, T. (2016). Action versus state orientation moderates the impact of executive functioning on real-life self-control. *Journal of Experimental Psychology: General*, 145, 1635–1653. <https://doi.org/10.1037/xge0000229>
- Yasuma, F., & Hayano, J. I. (2004). Respiratory sinus arrhythmia: Why does the heartbeat synchronize with respiratory rhythm? *Chest*, 125, 683–690. <https://doi.org/10.1378/chest.125.2.683>
- Zaccaro, A., Piarulli, A., Laurino, M., Garbella, E., Menicucci, D., Neri, B., & Gemignani, A. (2018). How breath-control can change your life: A systematic review on psychophysiological correlates of slow breathing. *Frontiers in Human Neuroscience*, 12. <https://doi.org/10.3389/fnhum.2018.00353>
- Zahn, D., Adams, J., Krohn, J., Wenzel, M., Mann, C. G., Gomille, L. K., Jacobi-Scherbening, V., & Kubiak, T. (2016). Heart rate variability and self-control—a meta-analysis. *Biological Psychology*, 115, 9–26. <https://doi.org/10.1016/j.biopsycho.2015.12.007>
- Zeigarnik, B. (1927). Über das Behalten erledigter und unerledigter Handlungen [About remembering completed and uncompleted actions]. *Psychologische Forschung*, 9, 1–85

## GENERAL INTRODUCTION

- Zelazo, P. D., & Carlson, S. M. (2012). Hot and cool executive function in childhood and adolescence: Development and plasticity. *Child Development Perspectives*, 6, 354–360. <https://doi.org/10.1111/j.1750-8606.2012.00246.x>
- Zimmermann-Viehoff, F., Thayer, J., Koenig, J., Herrmann, C., Weber, C. S., & Deter, H.-C. (2015). Short-term effects of espresso coffee on heart rate variability and blood pressure in habitual and non-habitual coffee consumers—a randomized crossover study. *Nutritional Neuroscience*, 19, 169–175. <https://doi.org/10.1016/10.1179/1476830515y.0000000018>
- Zucker, T. L., Samuelson, K. W., Muench, F., Greenberg, M. A., & Gevirtz, R. N. (2009). The effects of respiratory sinus arrhythmia biofeedback on heart rate variability and posttraumatic stress disorder symptoms: A pilot study. *Applied Psychophysiology and Biofeedback*, 34, 135–143. <https://doi.org/10.1007/s10484-009-9085-2>
- Zuckerman, M., Eysenck, S. B., & Eysenck, H. J. (1978). Sensation seeking in England and America: Cross-cultural, age, and sex comparisons. *Journal of Consulting and Clinical Psychology*, 46, 139–149. <https://doi.org/10.1037/0022-006x.46.1.139>

## **STUDY 1**

# **Action versus state orientation moderates the relation between executive function task performance and resting heart rate variability**

Daniel Groß

Groß, D. (2020). Action versus state orientation moderates the relation between executive function task performance and resting heart rate variability. *Journal of Research in Personality*, 86, 103936. <https://doi.org/10.1016/j.jrp.2020.103936>

**STUDY 2**  
**Predicting self-control capacity – Taking into account  
working memory capacity, motivation, and heart rate  
variability**

Daniel Groß & Carl-Walter Kohlmann

Groß, D., & Kohlmann, C.-W. (2020). Predicting self-control capacity – Taking into account working memory capacity, motivation, and heart rate variability. *Acta Psychologica*, 209, 103131. <https://doi.org/10.1016/j.actpsy.2020.103131>

## **STUDY 3**

# **Interventions to increase heart rate variability in healthy individuals: A 77-day study focusing on average resonance frequency training (6 breaths/minute) and progressive muscle relaxation**

Daniel Groß & Carl-Walter Kohlmann

Groß, D., & Kohlmann, C.-W. (2020). *Interventions to increase heart rate variability in healthy individuals: A 77-day study focusing on average resonance frequency training (6 breaths/minute) and progressive muscle relaxation*. Manuscript submitted for publication

**Abstract**

**Objective:** Higher heart rate variability (HRV) is associated with better health, self-control capacity and adaptability. This study examines, whether it is possible to increase HRV in healthy individuals (21 participants,  $M = 21.24$  years,  $SD = 1.57$ , range 19 to 26) through average resonance frequency training (RFT; 6 breaths per minute for 5 minutes each day) or progressive muscle relaxation (PMR; three times a week for 20 minutes) over 77 days.

**Design:** The effects were tested against an active control group using a linear mixed effect model with random slopes (day), and random intercepts (participants). **Main Outcome**

**Measure:** HRV was measured by the participants themselves each day in the morning using a mobile device. **Results:** The results indicated that the PMR group significantly increased their HRV compared to the active control group. No effect was observed for the RFT group.

**Conclusion:** Besides the non-effect, the non-significant effect of the average RFT group could be because the average RFT group had a significantly higher HRV compared to the active control group, which could not be further increased, or by the fact that the interventions differed in frequency and duration and the duration of a single average RFT session was too short.

*Keywords:* Heart rate variability; Intensive interventions; Resonance frequency training; Progressive muscle relaxation; Healthy individuals

## 1. Introduction

Heart rate variability (HRV), the change in the time intervals between two consecutive heartbeats (called RR [NN] intervals or interbeat intervals [IBIs]), is associated with better health, self-control capacity, increased executive functions, adaptability, and resilience (e.g., Lehrer et al., 2020; Segerstrom & Nes, 2007; Shaffer & Grinsberg, 2017; Thayer et al., 2009). In this article, we examine whether it is possible to increase HRV in healthy subjects through average resonance frequency training (RFT; for a systematic and *meta-analytic* review, see Lehrer et al., 2020) and progressive muscle relaxation (PMR; Jacobson, 1938) over 77 days.

### 1.1. Resonance frequency training

Average RFT aims to maximize the HRV through teaching the individual to breathe at 0.1 Hertz (Hz; 6 breaths per minute) to the point where breathing and the heart rate (HR) oscillate generally at the same resonance frequency (e.g., Gevirtz, 2013; Lehrer, 2013; Lehrer & Gevirtz, 2014; Lehrer et al., 2000; Vaschillo et al., 2006). HR oscillations do not normally occur at the same frequency as respiration. Generally, HR increases during inhalation since the cardiovascular center inhibits vagal tone<sup>62</sup> influence and decreases during exhalation since the cardiovascular center restores vagal outflow via the release of acetylcholine (this phenomenon is also known as respiratory sinus arrhythmia; e.g., Shaffer & Grinsberg, 2017; Yasuma & Hayano, 2004). HR and respiration only oscillate at the same resonance frequency when the normal breathing frequency, usually between 0.15 and 0.4 Hz (9 and 24 breaths per minute), is rhythmically stimulated by paced breathing at a frequency of 0.1 Hz. However, every person has a unique resonance frequency breathing rate, typically ranging between 4.5 and 6.5 breaths per minute. This individual breathing rate can be identified by asking a person to breathe at 4.5, 5.0, 5.5, 6.0, and 6.5 breaths per minute during HRV recording to find the breathing rate that

---

<sup>62</sup> The vagus nerve, the main parasympathetic nerve, influences the primary pacemaker of the heart leading to reduced HR and increased intervals between two consecutive heartbeats. In general, the HR is under tonic inhibitory control (e.g., Thayer et al., 2009).

### STUDY 3

results in the largest changes in HRV (i.e., where the current HRV is highest; originally done with frequency analysis, but it also works with time-domain analysis) which on average occurs at 0.1 Hz (e.g., Lehrer et al., 2000, 2003; Vaschillo et al., 2006). Breathing at 0.1 Hz also exercises the baroreflex to enhance context-specific regulation of blood pressure, leads to the most efficient gas exchange, and produces meditation or mindfulness related effects by focusing the attention on one's breathing (e.g., Gevirtz, 2013; Lehrer, 2013; Lehrer & Gevirtz, 2014; Yasuma & Hayano, 2004; for overviews of the psychophysiological mechanisms and effects of slow breathing techniques see Schwerdtfeger et al., 2019, Zaccaro et al., 2018, and Lehrer & Gevirtz, 2014). Several RFT studies have demonstrated that breathing at a rate of 0.1 Hz clinically improves symptoms of physical and mental disorders (for a summary, see Gevirtz, 2013) including asthma (Lehrer et al., 2004), Posttraumatic Stress Disorder (PTSD; e.g., Tan et al., 2011; Zucker et al., 2009), and depression (Karavidas et al., 2007; Siepmann et al., 2008; Tatschl et al., 2020). Most clinical studies exist for anxiety and cardiovascular disorders, where there is strong evidence of a small to medium effect of RFT (Lehrer et al., 2020). However, only a small number of studies have investigated the effect of RFT on HRV among healthy individuals, and the effects found are sometimes inconsistent. Siepmann and colleagues (2008) found that a 6-session RFT (duration of one session was 25 minutes) did not increase HRV among healthy individuals, whereas Lehrer and colleagues (2003) showed that a 10-session RFT (duration of one session was 30 minutes) increased HRV among healthy individuals. Two recently published studies further point to the potential of RFT to increase HRV in healthy individuals<sup>63</sup>. According to Steffen and colleagues (2017), even short unique RFT sessions (15 minutes) can have effects on HRV. In summary, however, the number of published studies is rather small and insufficient and HRV in intervention studies is not measured daily or over a

---

<sup>63</sup> Lin (2018) in a four-week intervention study (one hour weekly at the laboratory and 10 minutes homework daily), and Schumann and colleagues (2019) in an eight-week intervention study (five sessions; four sessions at home and one session at the laboratory; in their article the authors did not write how long a session lasted, but on request, the authors reported that one session lasted 2 x 11 minutes).

longer time, but mostly only at the beginning and end of the interventions. So the goal of this study is to bring more clarity, whether it is possible to increase HRV among healthy individuals through intensive average RFT while measuring HRV daily.

### ***1.2. Progressive muscle relaxation***

Another possible method to improve autonomic and cardiovascular effects is PMR (Jacobson 1938), which teaches individuals to reduce their muscle tone. Since muscles are part of the sympathetic nervous system the direct effect of PMR is to decrease the level of sympathetic arousal (thus the parasympathetic activity is indirectly increased), whereas RFT directly aims at strengthening the parasympathetic component (Lehrer et al., 2020). Focusing on study results, Pawlow and Jones (2002<sup>64</sup>) demonstrated that PMR reduces blood pressure and heart rate (HR), but the measurement was carried out immediately after the PMR session, so the outlasted effect of the PMR cannot be analyzed. Indeed Chaudhuri and colleagues (2014<sup>65</sup>) demonstrated this effect in highly stressed female health care professionals after practicing PMR for three months (participants were asked to do 20 minutes of PMR on their own each day), but they did not analyze men or no/low stressed females. Seckendorff (2009) examined this in his PhD thesis, indicating that a six-week training of PMR (6 x 60 minutes – under the guidance of a psychologist) did not have a significant effect on HR and HRV in healthy participants. Provided that the participants in the study of Chaudhuri and colleagues (2014) practiced PMR every day, they underwent a longer training of PMR (about 1800 minutes of PMR) in terms of quantity compared to the participants in the study conducted by Seckendorff (2009; about 360 minutes of PMR). Maybe the PMR training in the study of Seckendorff (2009) was too short (also in frequency) to find an effect on HRV. However, that even relatively short relaxation training (including PMR; one hour weekly in the laboratory and 10 minutes homework daily) can have positive effects on HRV was recently shown by Lin

---

<sup>64</sup> Did not test HRV.

<sup>65</sup> Did not test HRV.

(2018) in a four-week intervention. She also examined the effect of RFT and showed that participants in the RFT group increased HRV to a slightly greater degree than participants in the relaxation group. As already mentioned at the end of the previous RFT section, the study situation of PMR increasing HRV in healthy individuals is also rather small and insufficient, and HRV in intervention studies is not measured daily or over a longer time, but mostly only at the beginning and end of the interventions. So the goal of this study is to bring more clarity, whether it is possible to increase HRV among healthy individuals through intensive PMR training while measuring HRV daily.

### *1.3. Present study*

In the present study, we tested whether HRV improvements were also possible through average RFT and PMR among healthy individuals with no obvious autonomic nervous system (ANS) dysregulation. Most previous studies examined individuals who had ANS dysregulation (and consequently a compromised HRV), only analyzed the effect of a relatively short-term intervention, or measured HRV only twice before and after the interventions.

Focusing these limitations, we tested the effect of average RFT and PMR on the improvement in HRV over 77 days in healthy individuals. The effects of average RFT and PMR were tested against an active control group, which did a dual-task consisting of cognitive tasks and a motor task that was conducted at the same time. Participants used a mobile device to measure HRV every morning. Compared to the active control group, a significant increase in HRV was expected for both the average RFT group and the PMR group.

## **2. Methods**

### ***2.1. Participants***

Participants were composed of 21 students (16 female,  $M = 21.24$  years,  $SD = 1.57$ , range 19 to 26), so that each group, average RFT (seven females;  $M = 21.86$  years,  $SD = 0.64$ , range 21 to 23), PMR (five females;  $M = 20.14$  years,  $SD = 0.83$ , range 19 to 21), and dual-task (four females;  $M = 21.71$  years,  $SD = 2.12$ , range 19 to 26) consisted of seven participants, respectively. The participants were randomly assigned to the groups.

### ***2.2. Ethical consideration***

Before the experiment, participants received written informed consent, and we ensured them that their data would be treated confidentially. By participating in the study, the students could improve their grades in a seminar. However, they could also leave the study at any point in time and switch to a parallel seminar. The study was approved by the Ethics Committee of the university.

### ***2.3. Heart rate variability measurement***

For HRV measurement, we used the device and software of the Pulse7 GmbH (Vitalmonitor Pro, Austria) with a breast belt (sampling rate of 500 Hz – 1-Channel ECG), and a mobile phone app. One measurement took three minutes. The three-minute HRV measurement was divided into a spontaneous breathing phase and a short average RFT phase (i.e., each participant had a short average RFT, even though the participant wasn't part of the average RFT intervention group. This means that each participant has received a short average RFT training and a specific intervention). The spontaneous breathing phase took 110 seconds and the average RFT phase 70 seconds. During the measurement, which was supposed to be completed approximately 10 minutes after getting up in the morning, participants were asked not to speak or distract themselves. They were asked to sit on a chair with a backrest for each measurement so that minimal muscle tension was required to maintain the position. As an HRV parameter, we used the root mean square of the successive differences (RMSSD), which was

## STUDY 3

only calculated for the spontaneous breathing phase. Overall, 96 percent (range: 86–100 percent) of the daily measurements (77 days) were completed. The measurements were monitored daily, and in case of obvious measurement difficulties, communication with the participants was carried out via chat.

### ***2.4. Intervention groups and active control group***

#### ***2.4.1. Average resonance frequency training***

Participants of the average RFT group breathed at a frequency of about 0.1 Hz (5-sec inhalation and 5-sec exhalation) for five minutes on every day of the 77 days (overall 385 minutes). Average RFT was performed and observed with the device and software of the Pulse7 GmbH (Vitalmonitor Pro, Austria). Overall, 99 percent (range: 99–100 percent) of the average RFTs were completed.

#### ***2.4.2. Progressive muscle relaxation***

Participants of the PMR group practiced PMR three times a week for approximately 18 minutes (overall approximately 594 minutes). For the training, we used an audio file (short version with background music; German version) of the “Techniker Krankenkasse” (available under [www.tk.de/tk/gesunder-ruecken/entspannung-und-entlastung/jacobson/21538](http://www.tk.de/tk/gesunder-ruecken/entspannung-und-entlastung/jacobson/21538)). Once a week, all participants of this group practiced PMR together. The other two sessions were completed by the participants themselves and were observed and presented by the SoSci Panel, a service to create online questionnaires and studies ([www.soscisurvey.com](http://www.soscisurvey.com)). The PMR training started with guided instruction on breathing. Participants were then guided to contract the muscles in their right and left hands, as well as their arms, and were then asked to release tension after a few seconds. Participants were guided to repeat this contraction and relaxation ritual for three other muscle groups (the head, the trunk, and the right and left upper legs, calves, and feet). This was followed by some minutes of background music, where participants were invited

to imagine a beautiful place of rest (resting image). Overall, 99 percent (range: 94–100 percent) of the PMR trainings were completed.

#### ***2.4.3. Dual-task for the active control group<sup>5</sup>***

The dual-task consisted of four different cognitive tasks (primarily focusing on working memory), which were combined with a simultaneous motor task (participants had to keep their balance on a Moonhopper [balance board]). The cognitive tasks were presented by a video, and participants practiced three times a week for 20 minutes, respectively (overall: 660 minutes). Once a week, all participants practiced this together. The remaining sessions were completed by the participants themselves and were observed and presented by the SoSci Panel. Overall, 93 percent (range: 76–100 percent) of the dual-tasks were done.

#### ***2.5. Data analyzing and processing***

After downloading the RR intervals from the Pulse7 GmbH server, we analyzed the data with the Kubios heart rate variability analysis package (version 3.3.1; Tarvainen et al., 2014, 2017) to calculate the RMSSD. For HRV analysis, the first 10 seconds of each measurement was automatically removed by the software, so that in total, 100 seconds of the spontaneous breathing condition were analyzed. Because Vitalmonitor only records IBI, we used the automatic filter (threshold level: very low) offered by Kubios to detect RR intervals that differ “abnormally” from the normal mean RR interval, which may represent an artifact (Tarvainen et al., 2014, 2017). This procedure is commonly used, and in most cases considered sufficient, when data was recorded in rest conditions (Laborde et al., 2017). The calculated RMSSD values were ln transformed because of the non-normal distribution.

---

<sup>5</sup> This active control group could also indirectly influence HRV, but has no direct influence on the ANS (i.e., direct sympathetic and parasympathetic influence). The neurovisceral integration model (e.g. Thayer et al., 2009) indicates that working memory capacity may be linked to HRV due to the common neural base the prefrontal cortex. However, a recent study by De Simoni and von Bastian (2018) indicated that training interventions of working memory in young adults did neither enhance working memory capacity nor the working memory mechanisms assumed to underlie transfer. It is rather the case that repeated training only improves the development of stimuli-specific expertise and the use of paradigm-specific strategies.

### STUDY 3

This study was supposed to last 14 weeks, but due to travel (i.e., jetlag), longer periods of illnesses, and stress caused by the examination phase at the end of the semester, our study had to be reduced to 11 weeks.

A mixed-effect model, using random slopes (daily HRV measurement – these values were  $z$ -standardized), and random intercepts (participants), was calculated using R software version 3.6.2. (R Core Team, 2019). Since we used both random slopes and random intercepts for the analysis, the control of confounding variables was not as crucial for the interaction of daily HRV measurement and group. However, since we also wanted to test if the average RFT and PMR group differ in HRV from the active control group, we controlled for both age (HRV decreases with age; e.g., Abhishekh et al., 2013; Bonnemeier et al., 2003) and sex<sup>6</sup>.

For R-code and data see:  
[https://osf.io/b28zn/?view\\_only=d70e65dd93bd472d94db9a142d46b7bf](https://osf.io/b28zn/?view_only=d70e65dd93bd472d94db9a142d46b7bf)

### 3. Results

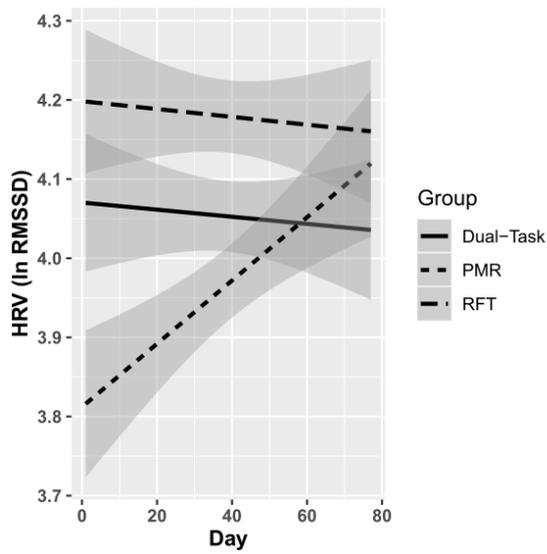
First of all, the mixed-effect model (see Table 1), using random slopes (daily HRV measurement) and random intercepts (participants), showed a main effect of the average RFT group,  $\beta = 0.25$ ,  $p = .045$ , indicating that this group had a significantly higher HRV than the active control group. Furthermore, the results showed a significant main effect of age,  $\beta = -0.08$ ,  $p = .034$ , and sex,  $\beta = 0.27$ ,  $p = .043$ , indicating that older participants generally had a lower HRV, and male participants in this sample generally had a higher HRV. Focusing on the effect of each intervention over time the results indicated that the PMR group significantly increased their HRV, compared to the active control group;  $\beta = 0.10$ ,  $p = .032$ . For the average RFT group, an increase in HRV could not be observed;  $\beta = 0.00$ ,  $p = .981$  (see Figure 1). To

---

<sup>6</sup> Generally, women tend to have greater vagal activity (higher HRV) than men, but according to a recently published *meta-analysis*, this is not reflected in the ln RMSSD parameter (Koenig & Thayer, 2016). But due to the small sample size we also controlled for sex.

### STUDY 3

illustrate the results more precisely, Figure 2 shows the HRV changes for each participant individually.



*Figure 1.* Time-varying effects of each group (dual-task; PMR = progressive muscle relaxation; RFT = average resonance frequency training); HRV = heart rate variability; Day = daily HRV measurement; grey shades correspond to the 95% confidence interval, respectively.

STUDY 3

Table 1

*Linear Mixed-Effect Model, using Resting HRV (ln RMSSD) as the Criterion.*

<i>Predictors</i>	<i>Estimates</i>	<i>CI</i>	<i>p</i>
(Intercept)	5.40	3.92 – 6.89	<b>&lt;0.001</b>
Day	–0.01	–0.08 – 0.05	0.696
PMR	–0.17	–0.41 – 0.07	0.175
RFT	0.25	0.01 – 0.50	<b>0.045</b>
Age	–0.08	–0.15 – –0.01	<b>0.034</b>
Sex	0.27	0.01 – 0.52	<b>0.043</b>
Day* PMR	0.10	0.01 – 0.19	<b>0.032</b>
Day* RFT	0.00	–0.09 – 0.09	0.982
<b>Random Effects</b>			
$\sigma^2$	0.22		
$\tau_{00}$ Participant	0.04		
$\tau_{11}$ Participant.Measurement	0.00		
$\rho_{01}$ Participant	–0.10		
ICC	0.17		
$N$ Participant	21		
Observations	1554		
Marginal $R^2$ / Conditional $R^2$	0.082 / 0.240		

*Note.* Results were tested against the active control group; women were coded as 1 and men as 2; HRV = heart rate variability; Day = daily HRV measurement; PMR = progressive muscle relaxation; RFT = average resonance frequency training.

le 1 *Linear Mixed-Effect Model, using Resting HRV (ln RMSSD) as the Criterion.*

### STUDY 3

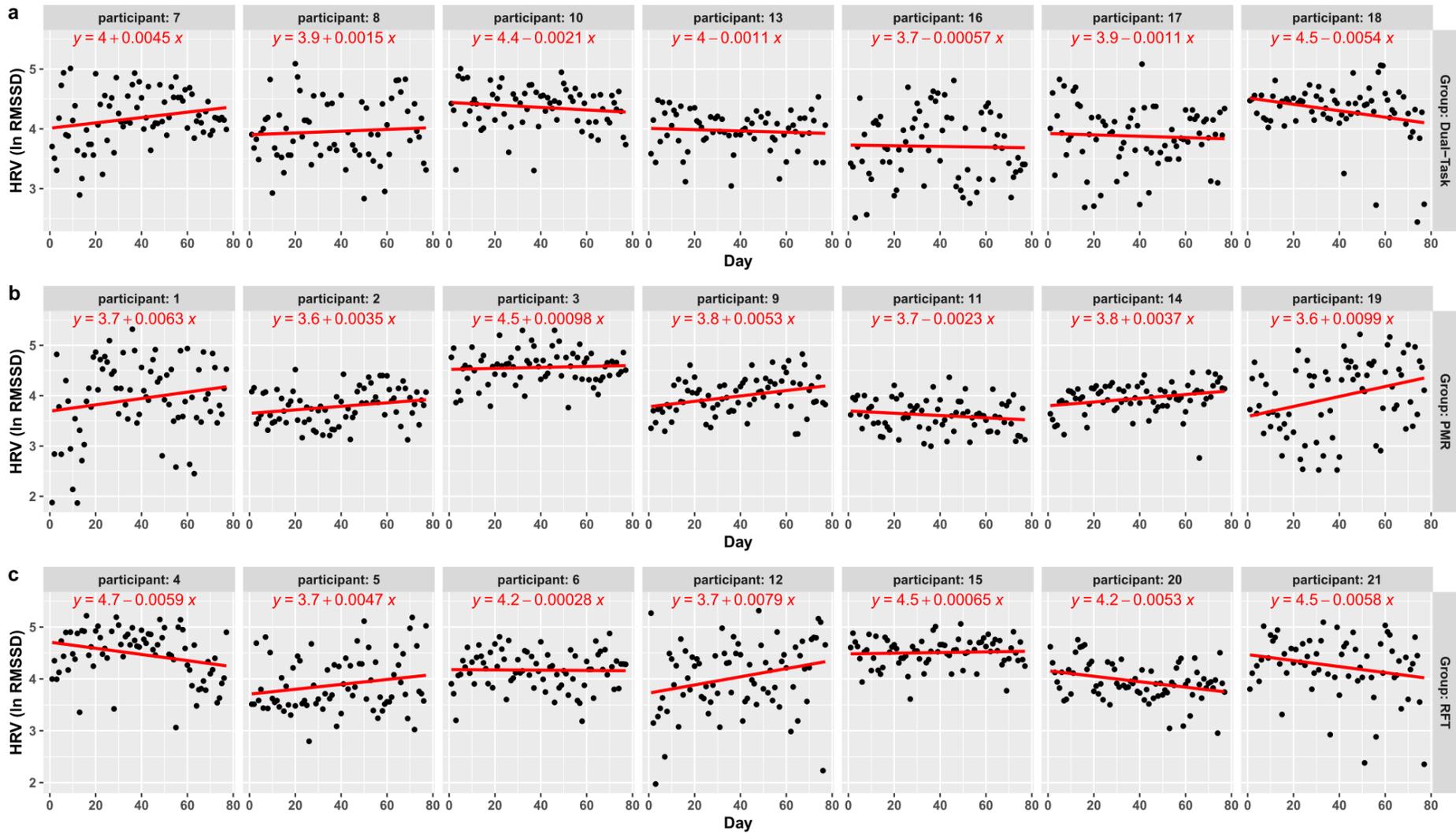


Figure 2. Daily HRV measurement of each participant; the graph also includes the individual linear equation (random effects) of each participant.

#### 4. Discussion

This study tested whether HRV improvements are possible in healthy individuals with no obvious ANS dysregulation through average RFT and PMR within 77 days while testing HRV daily. Such intensive measurement studies are rather rare since previous intervention studies often measured HRV only twice—at the beginning and end of the intervention. As far as we know, this is the first intervention study that measured HRV in healthy individuals daily.

First of all, focusing on the control variables, the result showed that men have a higher HRV than women, which is not in line with a *meta-analysis* on the sex effects of HRV (Koenig & Thayer, 2016)<sup>7</sup>. This might be the case since only five men were part of this study, which is not representative. Concerning the second control variable age, the result is in line with the finding that HRV decreases with age (e.g., Abhishekh et al., 2013; Bonnemeier et al., 2003).

Focusing on the effect of the interventions, the result indicated a significant increase in HRV (ln RMSSD) in the PMR group<sup>8</sup>, but not for the average RFT group. Therefore, the study indicates that frequent and long-term PMR training has the potential to increase HRV among healthy individuals. Here, the result seems to contradict the findings of Seckendorff (2009) regarding PMR (6 x 60 minutes), who found no HRV improvement but is in line with Lin (2018) who showed that relatively short relaxation training (including PMR; one hour weekly in the laboratory and 10 minutes homework daily for four weeks) had positive effects on HRV. However, Lin (2018) also analyzed the effect of RFT and showed that RFT increased HRV even to a slightly larger degree than relaxation training. In contrast, the average RFT in our study did not lead to an improvement in HRV. This might be the case since the average RFT group generally had a significantly higher HRV than the active control group. This explanation is in line with the results of Schumann and colleagues (2019), who showed that an eight-week

---

<sup>7</sup> Women generally tend to have greater HRV than men, but this is not reflected in the ln RMSSD parameter.

<sup>8</sup> PMR seems to indirectly increase parasympathetic activity by reducing sympathetic activity and not directly like RFT (Lehrer et al., 2020).

## STUDY 3

RFT training led to an increase in HRV, but that the training had no effect for individuals with high HRV. Therefore, it seems that especially individuals with low HRV benefit from (average) RFT. Another possible explanation for this result might be that we used average RFT instead of individual RFT, which might train the HRV better than only average RFT. What might also play a role in the effectiveness of interventions is that it is not clear today how much training is needed to increase HRV (i.e. the dose-effect relation). In this study, participants in the average RFT group breathed for 5 minutes daily. This might be a too short intervention regarding the duration of a single session (in most studies, single RFT sessions are often much longer than 5 minutes), even if the total duration of the intervention (385 minutes) was rather high. In the PMR group the participants had longer single sessions (about 18 minutes per session), and also the total duration of the intervention was longer (594 minutes) than in the average RFT group, both of which could potentially be reasons why there was an improvement in the PMR group and not in the average RFT group. Therefore, in subsequent studies, care should be taken to ensure that interventions have the same duration for every single session and in total, to be able to compare the interventions.

### *4.1. Limitations and some further proposals for subsequent studies*

Focusing on the effect of PMR it should be noted that perhaps not only the PMR training alone improved the HRV, but also the combination of PMR and the 70 seconds of average RFT in the daily HRV measurement. This possibility should be excluded in future studies. Also, subsequent studies can analyze the assumption that especially individuals with lower HRV benefit from the interventions, regardless of whether they do PMR or RFT. This study and also the study by Schumann and colleagues (2019) seem to indicate that healthy individuals with high HRV (in our study the RFT group) have difficulties in increasing HRV even further. The question that arises is whether this also applies to PMR when HRV is higher in individuals?

### STUDY 3

Furthermore, since it seems to be important for the effectiveness of RFT to focus on the breath and maintain the breathing rhythm (in this study 6 breaths per minute)<sup>9</sup>, the ability to consciously focus and maintain attention on breathing could be an important factor to improve an already high HRV. Further studies should test this presumption in more detail.

Moreover, in this study, we do not determine the unique individual resonance frequency breathing rate. Every participant in the average RFT group breath with 6 breaths per minute (inhalation-to-exhalation ratio of 5:5). Lin and colleagues (2014) indicated that slow breathing with both 6 and 5.5 breaths per minutes resulted in higher HRV indices compared with spontaneous breathing, but that 5.5 breaths per minute (here the inhalation-to-exhalation ratio of 5:5 is preferable to a ratio of 4:6) increases HRV indices even more than 6 breaths per minutes. Therefore, subsequent studies that do not determine the unique individual resonance frequency breathing rate, should consider using 5.5 breaths per minute for average RFT.

Future studies should also try to assess and control factors that impacted HRV more accurately, like the individual health status (e.g., physical pre-existing conditions, current illnesses), smoking (e.g., Daly et al., 2014), alcohol consumption (e.g., Karpyak et al., 2013), physical activity (e.g., Daly et al., 2014; Henje Blom et al., 2009; Stanley et al., 2013), and sleeping routine (e.g., Van Eekelen et al., 2004). Besides this, a more balanced sex ratio and a larger sample size should be used. Further studies should also investigate whether the results can be transferred to other populations outside the student population (e.g., elderly people).

Last but not least, further intense studies should also test whether a possible HRV improvement through an intervention is also reflected in variables such as health, self-control capacity, increased executive functions, adaptability, and resilience (cf. Segerstrom & Nes, 2007; Shaffer & Grinsberg, 2017; Thayer et al., 2009). Schumann and colleagues (2019) had

---

<sup>9</sup> Slow breathing can be uncomfortable during the first sessions and it can be difficult to maintain the breathing rhythm over the period of the intervention. This should also be pointed out to the participants.

recently shown that RFT can increase HRV but that this increase had no effect on measures of impulsivity. However, further intensive intervention studies are certainly needed to get a clearer picture of whether HRV interventions also affect other variables.

## 5. References

- Abhishekh, H. A., Nisarga, P., Kisan, R., Meghana, A., Chandran, S., Trichur Raju, & Sathyaprabha, T. N. (2013). Influence of age and gender on autonomic regulation of heart. *Journal of Clinical Monitoring and Computing*, 27, 259–264. <https://doi.org/10.1007/s10877-012-9424-3>
- Bonnemeier, H., Wiegand, U. K. H., Brandes, A., Kluge, N., Katus, H. A., Richardt, G., & Potratz, J. (2003). Circadian profile of cardiac autonomic nervous modulation in healthy subjects: Differing effects of aging and gender on heart rate variability. *Journal of Cardiovascular Electrophysiology*, 14, 791–799. <https://doi.org/10.1046/j.1540-8167.2003.03078.x>
- Chaudhuri, A., Ray, M., Saldanha, D., & Bandopadhyay, A. (2014). Effect of progressive muscle relaxation in female health care professionals. *Annals of Medical and Health Sciences Research*, 4, 791–795. <https://doi.org/10.4103/2141-9248.141573>
- Daly, M., Baumeister, R. F., Delaney, L., & MacLachlan, M. (2014). Self-control and its relation to emotions and psychobiology: Evidence from a day reconstruction method study. *Journal of Behavioral Medicine*, 37, 81–93. <https://doi.org/10.1007/s10865-012-9470-9>
- De Simoni, C., & von Bastian, C. C. (2018). Working memory updating and binding training: Bayesian evidence supporting the absence of transfer. *Journal of Experimental Psychology: General*, 147, 829–858. <https://doi.org/10.1037/xge0000453>
- Fatissou, J., Oswald, V., & Lalonde, F. (2016). Influence diagram of physiological and

### STUDY 3

- environmental factors affecting heart rate variability: An extended literature overview. *Heart International*, *11*, e32–e40. <https://doi.org/10.5301/heartint.5000232>
- Gevirtz, R. (2013). The promise of heart rate variability biofeedback: Evidence-based applications. *Biofeedback*, *41*, 110–120. <https://doi.org/10.5298/1081-5937-41.3.01>
- Henje Blom, E., Olsson, E. M. G., Serlachius, E., Ericson, M., & Ingvar, M. (2009). Heart rate variability is related to self-reported physical activity in a healthy adolescent population. *European Journal of Applied Physiology*, *106*, 877–883. <https://doi.org/10.1007/s00421-009-1089-3>
- Jacobson, E. (1938). *Progressive relaxation*. Chicago: University of Chicago press.
- Karavidas, M. K., Lehrer, P. M., Vaschillo, E., Vaschillo, B., Marin, H., Buyske, S., Malinovsky, I., Radvanski, D., & Hasset, A. (2007). Preliminary results of an open label study of heart rate variability biofeedback for the treatment of major depression. *Applied Psychophysiology and Biofeedback*, *32*, 19–30. <https://doi.org/10.1007/s10484-006-9029-z>
- Karpyak, V. M., Romanowicz, M., Schmidt, J. E., Lewis, K. A., & Bostwick, J. M. (2013). Characteristics of heart rate variability in alcohol-dependent subjects and nondependent chronic alcohol users. *Alcoholism: Clinical and Experimental Research*, *38*, 9–26. <https://doi.org/10.1111/acer.12270>
- Koenig, J., & Thayer, J. F. (2016). Sex differences in healthy human heart rate variability: A meta-analysis. *Neuroscience & Biobehavioral Reviews*, *64*, 288–310. <https://doi.org/10.1016/j.neubiorev.2016.03.007>
- Laborde, S., Mosley, E., & Mertgen, A. (2018). A unifying conceptual framework of factors associated to cardiac vagal control. *Heliyon*, *4*, e01002. <https://doi.org/10.1016/j.heliyon.2018.e01002>

### STUDY 3

- Laborde, S., Mosley, E., & Thayer, J. F. (2017). Heart rate variability and cardiac vagal tone in psychophysiological research—recommendations for experiment planning, data analysis, and data reporting. *Frontiers in Psychology, 8*. <https://doi.org/10.3389/fpsyg.2017.00213>
- Lehrer, P. (2013). How does heart rate variability biofeedback work? Resonance, the baroreflex, and other mechanisms. *Biofeedback, 41*, 26–31. <https://doi.org/10.5298/1081-5937-41.1.02>
- Lehrer, P. M., & Gevirtz, R. (2014). Heart rate variability biofeedback: How and why does it work? *Frontiers in Psychology, 5*. <https://doi.org/10.3389/fpsyg.2014.00756>
- Lehrer, P., Kaur, K., Sharma, A., Shah, K., Huseby, R., Bhavsar, J., & Zhang, Y. (2020). Heart rate variability biofeedback improves emotional and physical health and performance: A systematic review and meta analysis. *Applied Psychophysiology and Biofeedback, 45*, 109–129. <https://doi.org/10.1007/s10484-020-09466-z>
- Lehrer, P. M., Vaschillo, E., & Vaschillo, B. (2000). Resonant frequency biofeedback training to increase cardiac variability: Rationale and manual for training. *Applied Psychophysiology and Biofeedback, 25*, 177–191. <https://doi.org/10.1023/A:1009554825745>
- Lehrer, P. M., Vaschillo, E., Vaschillo, B., Lu, S.-E., Eckberg, D. L., Edelberg, R., Shih, W. J.; Lin, Y.; Kuusela, T. A.; Tahvanainen, K. U. O., & Hamer, R. M. (2003). Heart rate variability biofeedback increases baroreflex gain and peak expiratory flow. *Psychosomatic Medicine, 65*, 796–805. <https://doi.org/10.1097/01.psy.0000089200.81962.19>
- Lehrer, P. M., Vaschillo, E., Vaschillo, B., Lu, S.-E., Scardella, A., Siddique, M., & Habib, R. H. (2004). Biofeedback treatment for asthma. *Chest, 126*, 352–361. <https://doi.org/10.1378/chest.126.2.352>
- Lin, I.-M. (2018). Effects of a cardiorespiratory synchronization training mobile application on

### STUDY 3

- heart rate variability and electroencephalography in healthy adults. *International Journal of Psychophysiology*, *134*, 168–177. <https://doi.org/10.1016/j.ijpsycho.2018.09.005>
- Lin, I.-M., Tai, L. Y., & Fan, S. Y. (2014). Breathing at a rate of 5.5 breaths per minute with equal inhalation-to-exhalation ratio increases heart rate variability. *International Journal of Psychophysiology*, *91*, 206–211. <https://doi.org/10.1016/j.ijpsycho.2013.12.006>
- Pawlow, L. A., & Jones, G. E. (2002). The impact of abbreviated progressive muscle relaxation on salivary cortisol. *Biological Psychology*, *60*, 1–16. [https://doi.org/10.1016/s0301-0511\(02\)00010-8](https://doi.org/10.1016/s0301-0511(02)00010-8)
- R Core Team (2019). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. [www.R-project.org](http://www.R-project.org)
- Schumann, A., Köhler, S., Brotte, L., & Bär, K.-J. (2019). Effect of an eight-week smartphone-guided HRV-biofeedback intervention on autonomic function and impulsivity in healthy controls. *Physiological Measurement*, *40*, 064001. <https://doi.org/10.1088/1361-6579/ab2065>
- Schwerdtfeger, A. R., Schwarz, G., Pfurtscheller, K., Thayer, J. F., Jarczok, M. N., & Pfurtscheller, G. (2019). Heart rate variability (HRV): From brain death to resonance breathing at 6 breaths/minute. *Clinical Neurophysiology*, *131*, 676–693. <https://doi.org/10.1016/j.clinph.2019.11.013>
- Seckendorff, R. v. (2009). *Auswirkungen eines 6-wöchigen Entspannungstrainings (Progressive Muskelrelaxation nach Jacobson) auf Blutdruck, Herzfrequenz und Herzratenvariabilität sowie psychologische Parameter (Stresserleben, Angst, Ärger) bei gesunden Probanden [Effects of a 6-week relaxation training (progressive muscle relaxation according to Jacobson) on blood pressure, heart rate and heart rate variability as well as psychological parameters (stress, anxiety, anger) in healthy individuals]*.

### STUDY 3

(Doctoral dissertation Medizinischen Fakultät Charité Universitätsmedizin Berlin)

- Segerstrom, S. C., & Nes, L. S. (2007). Heart rate variability reflects self-regulatory strength, effort, and fatigue. *Psychological Science, 18*, 275–281. <https://doi.org/10.1111/j.1467-9280.2007.01888.x>
- Shaffer, F., & Ginsberg, J. P. (2017). An overview of heart rate variability metrics and norms. *Frontiers in Public Health, 5*. <https://doi.org/10.3389/fpubh.2017.00258>
- Siepmann, M., Aykac, V., Unterdörfer, J., Petrowski, K., & Mueck-Weymann, M. (2008). A pilot study on the effects of heart rate variability biofeedback in patients with depression and in healthy subjects. *Applied Psychophysiology and Biofeedback, 33*, 195–201. <https://doi.org/10.1007/s10484-008-9064-z>
- Stanley, J., Peake, J. M., & Buchheit, M. (2013). Cardiac parasympathetic reactivation following exercise: Implications for training prescription. *Sports Medicine, 43*, 1259–1277. <https://doi.org/10.1007/s40279-013-0083-4>
- Steffen, P. R., Austin, T., DeBarros, A., & Brown, T. (2017). The impact of resonance frequency breathing on measures of heart rate variability, blood pressure, and mood. *Frontiers in Public Health, 5*. <https://doi.org/10.3389/fpubh.2017.00222>
- Tan, G., Dao, T. K., Farmer, L., Sutherland, R. J., & Gevirtz, R. (2011). Heart rate variability (HRV) and posttraumatic stress disorder (PTSD): A pilot study. *Applied Psychophysiology and Biofeedback, 36*, 27–35. <https://doi.org/10.1007/s10484-010-9141-y>
- Tarvainen, M.P., Lipponen, J., Niskanen, J.P., Ranta-Aho, P. (2017). *Kubios HRV Version 3 – User’s Guide*. Kuopio: University of Eastern Finland.
- Tarvainen, M. P., Niskanen, J. P., Lipponen, J. A., Ranta-Aho, P. O., & Karjalainen, P. A. (2014). Kubios HRV–heart rate variability analysis software. *Computer Methods and Programs in Biomedicine, 113*, 210–220. <https://doi.org/10.1016/j.cmpb.2013.07.024>

### STUDY 3

- Tatschl, J. M., Hochfellner, S. M., & Schwerdtfeger, A. R. (2020). Implementing mobile HRV biofeedback as adjunctive therapy during inpatient psychiatric rehabilitation facilitates recovery of depressive symptoms and enhances autonomic functioning short-term: A 1-year pre–post-intervention follow-up pilot study. *Frontiers in Neuroscience, 14*, 738. <https://doi.org/10.3389/fnins.2020.00738>
- Thayer, J. F., Hansen, A. L., Saus-Rose, E., & Johnsen, B. H. (2009). Heart rate variability, prefrontal neural function, and cognitive performance: The neurovisceral integration perspective on self-regulation, adaptation, and health. *Annals of Behavioral Medicine, 37*, 141–153. <https://doi.org/10.1007/s12160-009-9101-z>
- Van Eekelen, A. P. J., Houtveen, J. H., & Kerkhof, G. A. (2004). Circadian variation in cardiac autonomic activity: Reactivity measurements to different types of stressors. *Chronobiology International, 21*, 107–129. <https://doi.org/10.1081/cbi-120027983>
- Vaschillo, E. G., Vaschillo, B., & Lehrer, P. M. (2006). Characteristics of resonance in heart rate variability stimulated by biofeedback. *Applied Psychophysiology and Biofeedback, 31*, 129–142. <https://doi.org/10.1007/s10484-006-9009-3>
- Yasuma, F., & Hayano, J. I. (2004). Respiratory sinus arrhythmia: Why does the heartbeat synchronize with respiratory rhythm? *Chest, 125*, 683–690. <https://doi.org/10.1378/chest.125.2.683>
- Zaccaro, A., Piarulli, A., Laurino, M., Garbella, E., Menicucci, D., Neri, B., & Gemignani, A. (2018). How breath-control can change your life: A systematic review on psychophysiological correlates of slow breathing. *Frontiers in Human Neuroscience, 12*. <https://doi.org/10.3389/fnhum.2018.00353>
- Zucker, T. L., Samuelson, K. W., Muench, F., Greenberg, M. A., & Gevirtz, R. N. (2009). The effects of respiratory sinus arrhythmia biofeedback on heart rate variability and

### STUDY 3

posttraumatic stress disorder symptoms: A pilot study. *Applied Psychophysiology and Biofeedback*, 34, 135–143. <https://doi.org/10.1007/s10484-009-9085-2>

**GENERAL DISCUSSION**

This dissertation aimed to shed some further light into the maze of self-control and self-regulation by taking self-ratings, executive functions (EFs), heart rate variability (HRV), and action-state orientation into account. For this purpose, three studies were conducted. In the following, the results of the studies are briefly presented and discussed, before a final statement follows.

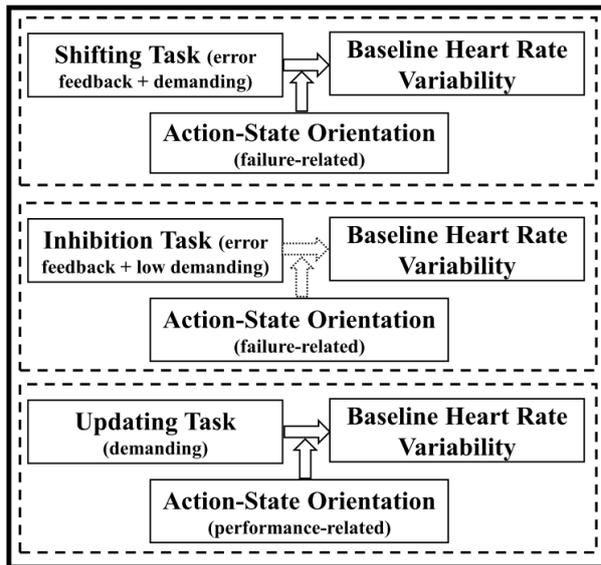
**1. Summary of the studies*****1.1. Study 1: Executive functions and heart rate variability***

Study 1 (see Figure 1) examined whether the relationship between EF task performance and resting vagally mediated HRV (both variables were  $z$ -standardized), based on the neurovisceral integration model (Thayer et al., 2009; Thayer & Lane, 2000, 2009), was moderated by implicit affect and attention regulation measured by action-state orientation (Kuhl, 1994a, 1994b) since two recent *meta-analyses* only indicated small effect sizes between HRV and EFs ( $r = .09$ , 123 studies, Holzman & Bridgett, 2017;  $r = .15$ , 26 studies, Zahn et al., 2016). For this purpose, HRV was measured once in all participants, before the participants had to conduct three EF tasks with different task characteristics (cognitive demands and error feedback). Study 1 indicated that the relationship tended to be moderated by action-state orientation, in two demanding EF tasks (shifting task:  $b = -0.08$ ,  $p = .005$ ; updating task:  $b = -0.08$ ,  $p = .025$ ), as well as in a low-demanding EF task (inhibition task:  $b = 0.05$ ,  $p = .082$ ). Depending on the availability of error feedback, either the failure-related action-state orientation (AOF-SOF) subscale (for the shifting task and inhibition task), or the performance-related action-state orientation (AOP-SOP) subscale (for the updating task) was expected to be the potential moderating variable. To highlight the difference between AOF-SOF and AOP-SOP, both subscales were included as moderators in each of the three analyses. Focusing on the Johnson Neyman test, the results only indicated a significant relationship for state-oriented

## GENERAL DISSCUSSION

individuals, which also differed in the direction between demanding and low-demanding EF task performance. On the one hand, this suggests that state-oriented individuals also use and mobilize their potential EF capacity (indicated by HRV), not necessarily to accomplish the EF task at hand, but instead, some EF capacity is consumed by error rumination (shifting task), or task-irrelevant thoughts (updating task). However, on the other hand, the results also indicated that state-oriented individuals could even outperform action-oriented individuals in low-demanding EF tasks, because error rumination helps them to better identify the target stimulus in the low-demanding inhibition task (only two stimuli needed to be distinguished; cf. Jostmann & Koole, 2006; Koole et al., 2005, 2012).

One reason for the non-significant relationship between EF task performance and resting HRV for action-oriented individuals might be that AOF individuals didn't manage to completely distance themselves from errors, especially in the shifting task where errors were presented visually and by a very unpleasant beep (cf. Koole et al., 2005). Another reason might be that individuals judged themselves to be more action-oriented than they are since they are subject to socially desirable responding (e.g., Diefendorff et al., 2000). Therefore, Study 1 provided a possible explanation for the low relationship between EFs and HRV as indicated by the *meta-analyses* (Holzman & Bridgett, 2017; Zahn et al., 2016), even though Study 1 could not completely confirm the neurovisceral integration model (Thayer et al., 2009; Thayer & Lane, 2000, 2009) due to the non-significant relationship for action-oriented individuals in the Johnson Neyman tests.



*Figure 1.* Graphical overview of Study 1; only the interactions are shown; significant interactions are shown with solid lines; the significant interactions became significant mainly because of the state-oriented individuals since the Johnson Neyman tests were not significant for action-oriented individuals.

### ***1.2. Study 2: Self-control capacity***

Study 2 (see Figure 2) investigated the interplay of control capacity and control motivation (indicated by demand-related action-state orientation [AOD-SOD]; Kuhl, 1994a, 1994b) on the prediction of state self-control (indicated by a Simon task after demanding EF tasks), as well as on trait self-control (indicated by the German brief version of the Self-Control Scale; Bertrams & Dickhäuser, 2009; Tangney et al., 2004). Control capacity was measured by working memory capacity (WMC) as proposed by the integrative theory of self-control (Kotabe & Hofmann, 2015), and Study 2 also tested the assumption of the vagal tank theory (Laborde et al., 2018) stating that control capacity can also be indexed by cardiac vagal control (measured by vagally mediated HRV). Furthermore, based on the vagal tank theory (Laborde et al., 2018), Study 2 also focused on within-subject changes of cardiac vagal control (baseline to post-event) as a possible index of state self-control capacity.

## GENERAL DISSCUSSION

In summary, the results of Study 2 corroborated the assumption of the integrative theory of self-control (Kotabe & Hofmann, 2015), stating that state ( $b = -0.22, p = .008$ ), as well as trait self-control ( $b = 0.15, p = .028$ ), can be predicted by an interplay of control capacity, indexed by WMC, and control motivation, indexed by AOD-SOD. However, only when focusing on state self-control capacity, a high score in one of these variables (high WMC or AOD) could compensate for a low score in the other component (low WMC or SOD) to maintain self-control. For trait self-control capacity AOD-SOD (highly significant main effect;  $b = 0.60, p < .001$ ) seemed to play a more important role than WMC. This might be because trait self-control, to a large extent, is also the result of the proactive development of temptation avoiding behavior (implementation and initiation of plans which often results in smart automatic habits; e.g., de Ridder et al., 2012; Ent et al., 2015). Developing these automatic habits might be easier for AOD individuals due to their higher general self-motivation.

When focusing on the possibility that control capacity for state, as well as for trait self-control can also be indexed by the between-subject analysis of cardiac vagal control, as proposed by the vagal tank theory (Laborde et al., 2018), the results were not quite as clear (the results only indicated a significant correlation between vagally mediated HRV and trait self-control capacity;  $r = .16, p = .044$ ). This might be because the trait and state components of HRV are different in size. Bertsch and colleagues (2012) found that about 30-40% of the variance in HRV measurements is due to the effects of the situation and person-situation interaction, and that about 50-60% of the variance is due to trait individual differences. Furthermore, the non-significant main effect of vagally mediated HRV in the regression analysis predicting trait self-control also indicated that there is a proportion of HRV that is already explained by action-state orientation, which might be the case since cardiac vagal control is also an objective marker of emotion regulation (e.g., Balzarotti et al., 2017), and action-oriented individuals have advantages in up-regulating positive affect (Kuhl, 1994a, 1994b).

Concerning the within-subject changes in cardiac vagal control, the results were much clearer, although the sample size here was much smaller. By combining the integrative theory of self-control (Kotabe & Hofmann, 2015) and the vagal tank theory (Laborde et al., 2018), the results indicated that primarily SOD individuals with a low WMC had a reduced cardiac vagal control and low recovery after the demanding EF tasks ( $b = -0.17, p = .018$ ). Therefore, Study 2 indicates that with regard to cardiac vagal control as an index of state self-control, it is better to analyze changes in cardiac vagal control (within-subject comparison), as compared to the analysis of between-subject differences in cardiac vagal control.

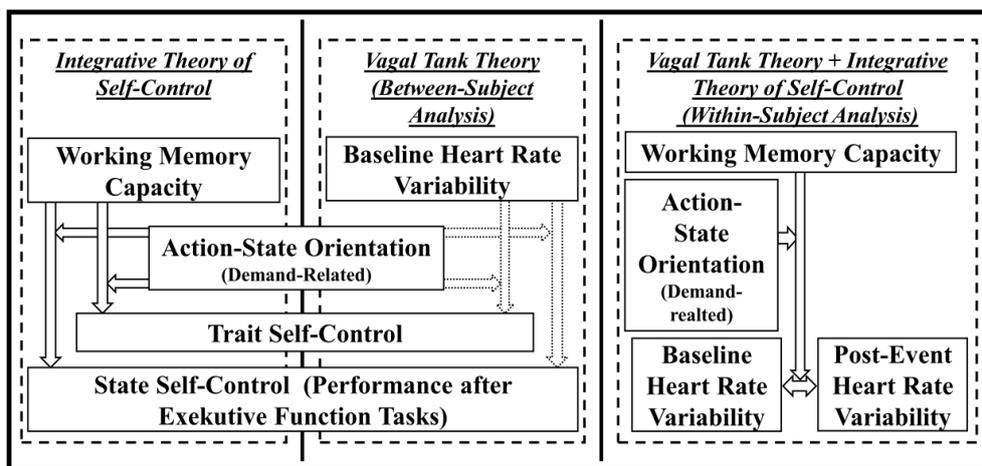


Figure 2. Graphical overview of Study 2; only the interactions are shown; significant interactions are shown with solid lines.

### 1.3. Study 3: Interventions to increase heart rate variability

Last but not least, Study 3 (see Figure 3) examined, whether it is possible to increase HRV in healthy individuals through average resonance frequency training (RFT; 6 breaths/minute for 5 minutes daily) or progressive muscle relaxation (PMR, three times a week for approximately 18 minutes respectively) over 77 days since increased HRV is associated with better health, self-control capacity<sup>66</sup>, increased EFs, adaptability, and resilience (e.g.,

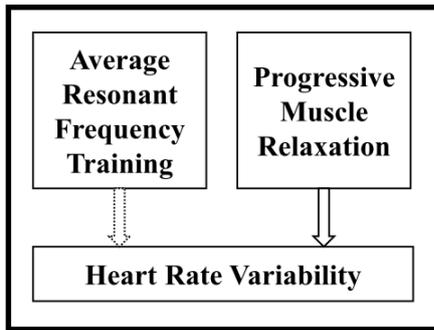
<sup>66</sup> Since self-control is also dependent on socialization, a higher HRV does not automatically mean that it is easier to wait and be patient. In resource-poor environments (i.e., the context of poverty), higher HRV (vagal tone) among children would predict shorter delay of gratification (i.e., taking the immediate reward; Sturge-Apple et al., 2016).

## GENERAL DISSCUSSION

Lehrer et al., 2020; Segerstrom & Nes, 2007; Shaffer & Grinsberg, 2017; Thayer et al., 2009) by using a mixed-effect model with random slopes (daily HRV measurement) and random intercepts (participants). The effects were tested against an active control group that completed a dual-task, consisting of a balance task with parallel cognitive tasks (three times a week for 20 minutes respectively) while controlling for age ( $\beta = -0.08$ ,  $p = .034$ ), and sex ( $\beta = 0.27$ ,  $p = .043$ )<sup>67</sup>, and HRV was measured by the participants themselves every morning using a mobile device. The results indicated a significant increase in HRV in the PMR group ( $\beta = 0.10$ ,  $p = .032$ ), but not for the RFT group ( $\beta = 0.00$ ,  $p = .981$ ). Therefore, the study showed that frequent and long-term PMR training had the potential to increase HRV among healthy individuals. Besides the non-effect, one reason for the lack of increase in HRV in the RFT group could be that the RFT group generally had significantly higher HRV compared to the control group, which could not be further increased (cf. Schumann et al., 2019), or by the fact that the average RFT (daily for 5 minutes respectively) and PMR (three times a week for approximately 18 minutes respectively) intervention differed in frequency and duration and that the duration of a single average RFT session was too short. Integrating the results of other studies (e.g., Lehrer et al., 2020; Lin, 2018; Schumann et al., 2019), it appears that PMR and RFT (individual RFT might have better effects instead of average RFT) can increase HRV but primarily in healthy individuals with rather reduced HRV (cf. Lehrer et al., 2020; Lin, 2018; Schumann et al., 2019).

---

<sup>67</sup> In this sample, older participants generally had a lower HRV, and male participants a higher HRV.



*Figure 3.* Graphical overview of Study 3; the intervention group with a significant effect is shown with a solid line.

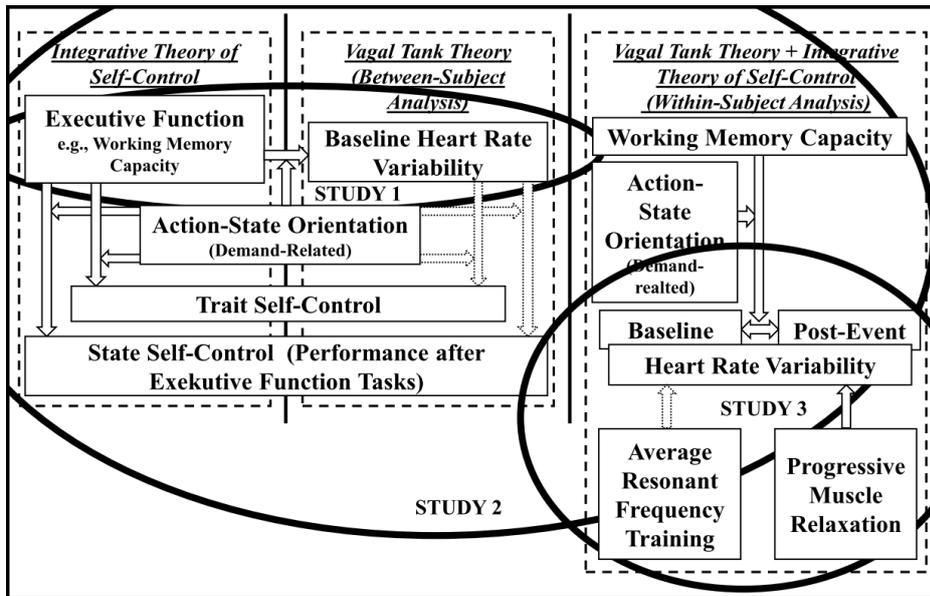
## 2. Final statement

This dissertation shed some further light into the maze of self-control and self-regulation by taking self-ratings, EFs, HRV, and action-state orientation into account.

Study 1 and Study 2 indicated the importance of taking action-state orientation, the implicit affect (positive affect = AOD-SOD, negative affect = AOF-SOF), and attention (AOP-SOP) regulation into account when analyzing the relation between EFs and HRV (Study 1; even though this study did not fully confirm the neurovisceral integration model; Thayer et al., 2009; Thayer & Lane, 2000, 2009) and by predicting state and trait self-control (Study 2; in this study, AOD-SOD represented self-motivation which interacted which control capacity, indexed by WMC; cf. Kotabe & Hofmann, 2015). Concerning HRV, Study 2 indicated that state self-control could best be indexed by within-subject changes in vagally mediated HRV, and that baseline resting HRV correlated, albeit very weakly, with trait self-control. Furthermore, Study 3 indicated that HRV can also be increased in healthy individuals. However, only significant increases for the PMR group were found. Possible explanations for the non-effect of the average RFT group were discussed and should be analyzed in further studies. Besides the assumption that the interventions are mainly effective in healthy individuals with reduced HRV, the

## GENERAL DISSCUSSION

influence of personality factors (e.g., motivation) in HRV interventions should also get more focus in subsequent studies.



*Figure 4.* Graphical overview of all three studies; only the interactions are shown; significant interactions are shown with solid lines.

In general, further investigations should also attempt to confirm the results found in the three studies of this dissertation. Primarily, the within-subject HRV analyses in Study 2, and the intervention study (Study 3), should be carried out with a larger number of subjects in subsequent studies to examine how reliable the findings are. Furthermore, subsequent studies should investigate the assumptions (demanding EF tasks where so stressful, that they exceeded even the profound affect and attention regulation capacity of action-oriented individuals [cf. Koole et al., 2005] or being action-oriented is significantly associated with socially desirable responding [Diefendorff et al., 2000]), why Study 1 could not completely confirm the neurovisceral integration model (Thayer et al., 2009; Thayer & Lane, 2000, 2009) in more detail. These results might also bring more clarity for the association of different self-control measurements in general. Indeed, the three studies of this dissertation (see Figure 4, for an overview of the studies) shed some light into the maze of self-control and self-regulation, which is studied, largely in parallel, in the field of social and personality psychology, cognitive

## GENERAL DISSCUSSION

psychology, and also in biology (e.g., Hofmann et al., 2012; Malanchini et al., 2019; Willems et al., 2019). However, there are many open questions, some of which are mentioned below as examples.

First of all, it is generally problematic for self-control and self-regulation research (and the related constructs such as impulsivity) that there are no uniform definitions and measurement methods. Future research should try to get more clarity and unity, even if this is a huge challenge because of different research directions and traditions. Future research should also distinguish even more clearly between state and trait self-control. A question that still needs to be clarified in more detail is how state and trait self-control are associated. Some studies indicate that high trait self-control is associated with greater state self-control (e.g., DeWall et al., 2007), whereas others detect the opposite result and interpret it in such a way that individuals with high trait self-control have less experience with direct self-control conflicts (e.g., Imhoff et al., 2014).

Furthermore, future research should also investigate whether it might be more appropriate for the promotion and improvement of EFs (because the far transfer effect on to untrained cognitive skills and even the near transfer effect seems to be narrow or does not even exist when focusing on the factor structure of EFs) to change the perspective on EFs, as suggested by Doebel (2020), and consider EFs as skills of practicing control in the service of specific goals that can be improved by knowledge, norms, and value-based training. Moreover, as mentioned earlier as a possibility for subsequent HRV intervention studies, personality traits (e.g., motivation) might also be included in the analysis of EFs improvement, especially when trying to improve EFs from a factorial perspective.

Subsequent studies should also investigate the effect of personality traits regarding the effectiveness of RFT and explore the possibility that healthy individuals with a high HRV might have greater difficulties in increasing their HRV through both PMR and RFT than healthy

individuals with a low HRV. Furthermore, future studies should also test whether a possible HRV improvement through an intervention is reflected in variables such as health, self-control capacity, impulsivity, increased EFs, adaptability, and resilience (cf. Segerstrom & Nes, 2007; Shaffer & Grinsberg, 2017; Thayer et al., 2009). Although, Schumann and colleagues (2019) have recently shown that RFT can increase HRV and that this increase has no effect on measures of impulsivity, but further intensive intervention studies are certainly needed here to obtain a clearer picture of whether HRV interventions also affect other variables (e.g., health, self-control capacity, impulsivity, EFs, adaptability).

As the last example for future research, it could also be analyzed in more detail whether the beneficial effect of AOD individuals on state self-control and ego depletion is due to motivation (i.e., better positive affect regulation; Gröpel et al., 2014) or more due to improved adaptation (e.g., Dang et al., 2014). Overall, this dissertation has expanded the research on self-control and self-regulation and brought more clarity, even if many questions remain open in the maze of self-control and self-regulation.

### 3. References general discussion

- Balzarotti, S., Biassoni, F., Colombo, B., & Ciceri, M. R. (2017). Cardiac vagal control as a marker of emotion regulation in healthy adults: A review. *Biological Psychology, 130*, 54–66. <https://doi.org/10.1016/j.biopsycho.2017.10.008>.
- Bertrams, A., & Dickhäuser, O. (2009). Messung dispositioneller Selbstkontroll-Kapazität [Measurement of trait self-control capacity]. *Diagnostica, 55*, 2–10. <https://doi.org/10.1026/0012-1924.55.1.2>
- Bertsch, K., Hagemann, D., Naumann, E., Schachinger, H., & Schulz, A. (2012). Stability of heart rate variability indices reflecting parasympathetic activity. *Psychophysiology, 49*, 672–682. <https://doi.org/10.1111/j.1469-8986.2011.01341.x>

## GENERAL DISSCUSSION

- Dang, J., Xiao, S., Shi, Y., & Mao, L. (2014). Action orientation overcomes the ego depletion effect. *Scandinavian Journal of Psychology*, *56*, 223–227. <https://doi.org/10.1111/sjop.12184>
- de Ridder, D. T. D., Lensvelt-Mulders, G., Finkenauer, C., Stok, F. M., & Baumeister, R. F. (2012). Taking stock of self-control: A meta-analysis of how trait self-control relates to a wide range of behaviors. *Personality and Social Psychology Review*, *16*, 76–99. <https://doi.org/10.1177/1088868311418749>
- DeWall, C. N., Baumeister, R. F., Stillman, T. F., & Gailliot, M. T. (2007). Violence restrained: Effects of self-regulation and its depletion on aggression. *Journal of Experimental Social Psychology*, *43*, 62–76. <https://doi.org/10.1016/j.jesp.2005.12.005>
- Diefendorff, J. M., Hall, R. J., Lord, R. G., & Streat, M. L. (2000). Action–state orientation: Construct validity of a revised measure and its relationship to work-related variables. *Journal of Applied Psychology*, *85*, 250–263. <https://doi.org/10.1037/0021-9010.85.2.250>
- Doebel, S. (2020). Rethinking executive function and its development. *Perspectives on Psychological Science*, *15*, 942–956. <https://doi.org/10.1177/1745691620904771>
- Ent, M. R., Baumeister, R. F., & Tice, D. M. (2015). Trait self-control and the avoidance of temptation. *Personality and Individual Differences*, *74*, 12–15. <https://doi.org/10.1016/j.paid.2014.09.031>
- Gröpel, P., Baumeister, R. F., & Beckmann, J. (2014). Action versus state orientation and self-control performance after depletion. *Personality and Social Psychology Bulletin*, *40*, 476–487. <https://doi.org/10.1177/0146167213516636>
- Hofmann, W., Schmeichel, B. J., & Baddeley, A. D. (2012). Executive functions and self-regulation. *Trends in Cognitive Sciences*, *16*, 174–180. <https://doi.org/10.1016/j.tics.2012.01.006>

## GENERAL DISSCUSSION

- Holzman, J. B., & Bridgett, D. J. (2017). Heart rate variability indices as bio-markers of top-down self-regulatory mechanisms: A meta-analytic review. *Neuroscience & Biobehavioral Reviews*, *74*, 233–255. <https://doi.org/10.1016/j.neubiorev.2016.12.032>
- Imhoff, R., Schmidt, A. F., & Gerstenberg, F. (2014). Exploring the interplay of trait self-control and ego depletion: Empirical evidence for ironic effects. *European Journal of Personality*, *28*, 413–424. <https://doi.org/10.1002/per.1899>
- Jostmann, N. B., & Koole, S. L. (2006). On the waxing and waning of working memory: Action orientation moderates the impact of demanding relationship primes on working memory capacity. *Personality and Social Psychology Bulletin*, *32*, 1716–1728. <https://doi.org/10.1177/0146167206292595>
- Koole, S. L., Jostmann, N. B., & Baumann, N. (2012). Do demanding conditions help or hurt self-regulation? *Social and Personality Psychology Compass*, *6*, 328–346. <https://doi.org/10.1111/j.1751-9004.2012.00425.x>
- Koole, S. L., Kuhl, J., Jostmann, N. B., & Vohs, K. D. (2005). On the hidden benefits of state orientation: Can people prosper without efficient affect regulation skills? In A. Tesser, J. Wood, & D. A. Stapel (Eds.), *On building, defending, and regulating the self: A psychological perspective* (pp. 217–243). London, UK: Taylor & Francis.
- Kotabe, H. P., & Hofmann, W. (2015). On integrating the components of self-control. *Perspectives on Psychological Science*, *10*, 618–638. <https://doi.org/10.1177/1745691615593382>
- Kuhl, J. (1994a). A theory of action and state orientations. In J. Kuhl & J. Beckmann (Eds.), *Volition and personality: Action versus state orientation* (pp. 9–46). Göttingen, Germany: Hogrefe & Huber Publishers.
- Kuhl, J. (1994b). Action versus state orientation: Psychometric properties of the Action Control

## GENERAL DISSCUSSION

- Scale (ACS-90). In J. Kuhl & J. Beckmann (Eds.), *Volition and personality: Action versus state orientation* (pp. 47–59). Göttingen, Germany: Hogrefe & Huber Publishers.
- Laborde, S., Mosley, E., & Mertgen, A. (2018). Vagal tank theory: The three Rs of cardiac vagal control functioning—resting, reactivity, and recovery. *Frontiers in Neuroscience, 12*. <https://doi.org/10.3389/fnins.2018.00458>
- Lehrer, P., Kaur, K., Sharma, A., Shah, K., Huseby, R., Bhavsar, J., & Zhang, Y. (2020). Heart rate variability biofeedback improves emotional and physical health and performance: A systematic review and meta analysis. *Applied Psychophysiology and Biofeedback, 45*, 109–129. <https://doi.org/10.1007/s10484-020-09466-z>
- Lin, I.-M. (2018). Effects of a cardiorespiratory synchronization training mobile application on heart rate variability and electroencephalography in healthy adults. *International Journal of Psychophysiology, 134*, 168–177. <https://doi.org/10.1016/j.ijpsycho.2018.09.005>
- Malanchini, M., Engelhardt, L. E., Grotzinger, A. D., Harden, K. P., & Tucker-Drob, E. M. (2019). “Same but different”: Associations between multiple aspects of self-regulation, cognition, and academic abilities. *Journal of Personality and Social Psychology, 117*, 1164–1188. <https://doi.org/10.1037/pspp0000224>
- Schumann, A., Köhler, S., Brotte, L., & Bär, K.-J. (2019). Effect of an eight-week smartphone-guided HRV-biofeedback intervention on autonomic function and impulsivity in healthy controls. *Physiological Measurement, 40*, 064001. <https://doi.org/10.1088/1361-6579/ab2065>
- Seegerstrom, S. C., & Nes, L. S. (2007). Heart rate variability reflects self-regulatory strength, effort, and fatigue. *Psychological Science, 18*, 275–281. <https://doi.org/10.1111/j.1467-9280.2007.01888.x>
- Shaffer, F., & Ginsberg, J. P. (2017). An overview of heart rate variability metrics and norms.

## GENERAL DISSCUSSION

*Frontiers in Public Health*, 5. <https://doi.org/10.3389/fpubh.2017.00258>

- Sturge-Apple, M. L., Suor, J. H., Davies, P. T., Cicchetti, D., Skibo, M. A., & Rogosch, F. A. (2016). Vagal tone and children's delay of gratification: Differential sensitivity in resource-poor and resource-rich environments. *Psychological Science*, 27, 885–893. <https://doi.org/10.1177/0956797616640269>
- Tangney, J. P., Baumeister, R. F., & Boone, A. L. (2004). High self-control predicts good adjustment, less pathology, better grades, and interpersonal success. *Journal of Personality*, 72, 271–324. <https://doi.org/10.1111/j.0022-3506.2004.00263.x>
- Thayer, J. F., Hansen, A. L., Saus-Rose, E., & Johnsen, B. H. (2009). Heart rate variability, prefrontal neural function, and cognitive performance: The neurovisceral integration perspective on self-regulation, adaptation, and health. *Annals of Behavioral Medicine*, 37, 141–153. <https://doi.org/10.1007/s12160-009-9101-z>
- Thayer, J. F., & Lane, R. D. (2000). A model of neurovisceral integration in emotion regulation and dysregulation. *Journal of Affective Disorders*, 61, 201–216. [https://doi.org/10.1016/s0165-0327\(00\)00338-4](https://doi.org/10.1016/s0165-0327(00)00338-4)
- Thayer, J. F., & Lane, R. D. (2009). Claude Bernard and the heart–brain connection: Further elaboration of a model of neurovisceral integration. *Neuroscience & Biobehavioral Reviews*, 33, 81–88. <https://doi.org/10.1016/j.neubiorev.2008.08.004>
- Willems, Y. E., Boesen, N., Li, J., Finkenauer, C., & Bartels, M. (2019). The heritability of self-control: A meta-analysis. *Neuroscience & Biobehavioral Reviews*, 100, 324–334. <https://doi.org/10.1016/j.neubiorev.2019.02.012>
- Zahn, D., Adams, J., Krohn, J., Wenzel, M., Mann, C. G., Gomille, L. K., Jacobi-Scherbening, V., & Kubiak, T. (2016). Heart rate variability and self-control—a meta-analysis. *Biological Psychology*, 115, 9–26. <https://doi.org/10.1016/j.biopsycho.2015.12.007>