Measuring Momentary Cognitive Functioning at Work:

The Validation of Short Smartphone-Based Cognitive Performance Tests and Their Exemplary Application in Two Occupational Diary Studies

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CONTENTS

CONTRIBUTIONS BASED ON THIS DISSERTATION

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SUMMARY

Job performance is a fundamental concept in industrial and organizational psychology that substantially fluctuates across and within workdays. However, momentary job performance is hard to capture in diary studies, particularly in white-collar work. In this dissertation, I propose cognitive functioning as a proxy for employees' performance capacity, which is closely linked to job performance. Cognitive functioning fluctuates at work and can be objectively measured with cognitive performance tests independent of employees' professions. In three diary studies, I addressed the research question of whether short smartphone-based versions of three established cognitive performance tests—the Digit Symbol Substitution Task (DSST), the Psychomotor Vigilance Task (PVT), and the Sustained Attention to Response Task (SART)—provide reliable, valid, feasible, and utile means to assess momentary cognitive functioning at work.

In the first empirical study, I aimed to identify the shortest measurement durations of the three cognitive performance tests that allow for reliable and valid smartphone-based measurements of momentary cognitive functioning in diary studies. Over a period of two weeks, 46 university students completed each cognitive performance test (DSST, PVT, SART) with a measurement duration of approximately three minutes once a day at random times combined with self-report items, providing 559–575 momentary assessments per test. Results for proportional test segments suggest a satisfying reliability of change from a measurement duration of 90 seconds onwards for the DSST and SART and from a measurement duration of 30 seconds onwards for the PVT. Significant within-person associations indicate that both the adapted DSST and SART are sensitive to fluctuating work demands, and the SART is sensitive to recovery. In contrast, work demands and recovery did not correlate with PVT performance, and results suggest a lack of motivation among participants to complete the PVT. Hence, I deemed the 90-second DSST and SART as promising tools to measure cognitive functioning in occupational diary studies, while I did not further pursue the application of the PVT in the context of work demands and recovery.

In the second empirical study, I aimed to demonstrate the feasibility and utility of the 90-second DSST for occupational diary studies by investigating within-person associations of morning challenge and hindrance stressors with cognitive functioning at three times during work (before the lunch break, after the lunch break, and at the end of work). To shed light on the role of recovery for work demands–cognitive functioning relations, I considered lunch break recovery (break duration, break detachment) as a moderator of lagged associations between morning work demands and afternoon cognitive functioning. Sixty-three knowledge workers completed smartphone questionnaires containing the 90-second DSST three times a day over two work weeks, providing 443 state assessments before the lunch break, 414 after the lunch break, and 426 at the end of the workday.

While morning hindrance stressors were not significantly associated with cognitive functioning at work, multilevel analyses revealed that morning challenge stressors were associated with better cognitive performance before the lunch break. Furthermore, lunch break recovery moderated the lagged associations of morning challenge stressors with afternoon cognitive functioning. On days with longer lunch break durations than usual, morning challenge stressors were positively associated with cognitive functioning after the lunch break and at the end of work. On days with higher lunch break detachment than usual, morning challenge stressors were positively associated with cognitive functioning at the end of work but not immediately after the lunch break. Opposing negative effects were found on days with shorter lunch break duration or less lunch break detachment than usual. Capturing the resource dependence of resource-mobilizing effects of challenge stressors and the resource-managing potential of lunch break recovery, these results strengthen the validity and utility of the adapted DSST for assessing cognitive functioning at work.

In the third empirical study, I aimed to demonstrate the feasibility and utility of the 90-second SART for occupational diary studies by testing the association between psychological (fatigue) and physiological (heart rate variability; HRV) evening recovery processes and cognitive functioning at the start of work the next morning. On three workdays, 65 employees continuously wore a dry electrode chest belt with electrocardiogram (ECG) sensors to extract HRV, responded to hourly smartphone questionnaires in between the end of work and bedtime, and completed the adapted SART the next morning at the beginning of the workday, providing data on 200 evenings and 185 mornings. Latent growth curve models support the assumed U-shaped psychological and physiological evening recovery trajectories. Furthermore, fatigue trajectories with a longer decrease before a circadian increase and HRV trajectories with a more immediate increase after the end of work were positively associated with next-morning cognitive functioning. Demonstrating the positive association between psychophysiological evening recovery and cognitive functioning at the start of work, these results support the validity and utility of the adapted SART to assess cognitive functioning in occupational diary studies.

Overall, this dissertation introduces the adapted DSST and SART as reliable, valid, and feasible tools to assess momentary cognitive functioning as a proxy of employees' performance capacity at work. Significant associations of work demands and recovery with momentary cognitive functioning underscore the tests' utility in occupational diary studies. Hence, researchers can consider the short smartphone-based DSST and SART as viable tools providing objective behavioral performance indicators. The cognitive performance tests may be particularly useful for diary studies focusing on samples that lack behavioral indicators of momentary job performance.

ZUSAMMENFASSUNG

Die Arbeitsleistung ist ein zentrales Konzept der Arbeits- und Organisationspsychologie, das zwischen und innerhalb von Arbeitstagen erheblichen Schwankungen unterliegt. Die momentane Arbeitsleistung lässt sich jedoch in Tagebuchstudien nur schwer erfassen, insbesondere in Arbeitskontexten mit primär mentalen Anforderungen. In dieser Dissertation schlage ich die Leistung in kognitiven Tests als Indikator für die kognitive Leistungsfähigkeit von Beschäftigten vor, die eng mit der Arbeitsleistung verbunden ist. Die kognitive Leistungsfähigkeit schwankt am Arbeitsplatz und lässt sich unabhängig vom Beruf objektiv messen. In drei Tagebuchstudien ging ich der Forschungsfrage nach, ob kurze, smartphone-basierte Versionen von drei etablierten kognitiven Leistungstests –Digit Symbol Substitution Task (DSST), Psychomotor Vigilance Task (PVT) und Sustained Attention to Response Task (SART) – reliable, valide, praktikable und nützliche Mittel zur Beurteilung der momentanen kognitiven Leistungsfähigkeit am Arbeitsplatz darstellen.

In der ersten empirischen Studie war es mein Ziel, die kürzesten Messdauern der drei kognitiven Leistungstests zu ermitteln, die reliable und valide smartphone-basierte Messungen der momentanen kognitiven Leistungsfähigkeit in Tagebuchstudien ermöglichen. Über einen Zeitraum von zwei Wochen absolvierten 46 Studierende jeden kognitiven Leistungstest (DSST, PVT, SART) mit einer Messdauer von etwa drei Minuten einmal täglich zu zufälligen Zeitpunkten in Kombination mit Selbstauskunftsfragen, wodurch 559–575 situative Messungen pro Test erzielt wurden. Die Ergebnisse für anteilige Testsegmente deuten auf eine zufriedenstellende Reliabilität der Messung situativer Schwankungen der kognitiven Leistungsfähigkeit ab einer Messdauer von 90 Sekunden für den DSST und den SART sowie ab einer Messdauer von 30 Sekunden für den PVT hin. Signifikante situative Zusammenhänge zeigen, dass der adaptierte DSST und SART sensitiv sind bezüglich schwankender Arbeitsanforderungen und der SART zudem sensitiv schwankende Erholung abbilden kann. Im Gegensatz dazu korrelierten Arbeitsanforderungen und Erholung nicht mit

der Leistung im PVT, und die Ergebnisse deuten auf eine mangelnde Motivation der Teilnehmenden hin, den PVT zu absolvieren. Daher erachtete ich den 90-sekündigen DSST und SART als vielversprechende Instrumente zur Messung der kognitiven Leistungsfähigkeit in arbeitsbezogenen Tagebuchstudien, während ich die Anwendung des PVT im Kontext von Arbeitsanforderungen und Erholung nicht weiter verfolgte.

In der zweiten empirischen Studie wollte ich die Praktikabilität und Nützlichkeit des 90-sekündigen DSST für arbeitsbezogene Tagebuchstudien aufzeigen, indem ich die intraindividuellen Zusammenhänge von Herausforderungen und Hindernissen am Vormittag mit der kognitiven Leistungsfähigkeit zu drei Zeitpunkten während der Arbeit (vor der Mittagspause, nach der Mittagspause und am Ende der Arbeit) untersuchte. Um die Rolle der Erholung für die Beziehungen zwischen Arbeitsanforderungen und kognitiver Leistungsfähigkeit zu beleuchten, betrachtete ich die Erholung während der Mittagspause (Pausendauer, Abschalten von der Arbeit) als Moderator für verzögerte Zusammenhänge zwischen Arbeitsanforderungen am Vormittag und der kognitiven Leistungsfähigkeit am Nachmittag. Dreiundsechzig Wissensarbeitende füllten über zwei Arbeitswochen hinweg dreimal täglich Smartphone-Fragebögen aus, die den 90-sekündigen DSST enthielten, und lieferten damit 443 situative Messungen vor der Mittagspause, 414 nach der Mittagspause und 426 am Ende des Arbeitstages.

Während Hindernisse am Vormittag keinen signifikanten Zusammenhang mit der kognitiven Leistungsfähigkeit am Arbeitsplatz aufwiesen, zeigten Mehrebenenanalysen, dass Herausforderungen am Vormittag mit einer besseren kognitiven Leistungsfähigkeit vor der Mittagspause verbunden waren. Darüber hinaus moderierte die Erholung während der Mittagspause die verzögerten Zusammenhänge zwischen Herausforderungen am Vormittag und der kognitiven Leistungsfähigkeit am Nachmittag. An Tagen mit einer längeren Mittagspause als üblich standen Herausforderungen am Vormittag in einem positiven Zusammenhang mit der kognitiven Leistungsfähigkeit nach der Mittagspause und am Ende des Arbeitstages. An Tagen mit stärkerem Abschalten von der Arbeit während der Mittagspause als üblich standen Herausforderungen am Vormittag in einem positiven Zusammenhang mit der kognitiven Leistungsfähigkeit am Ende des Arbeitstages, jedoch nicht unmittelbar nach der Mittagspause. An Tagen mit einer kürzeren Mittagspause oder einem geringeren Abschalten von der Arbeit während der Mittagspause als üblich wurden gegenteilige negative Effekte festgestellt. Diese Ergebnisse unterstreichen die Ressourcenabhängigkeit der ressourcenmobilisierenden Effekte von Herausforderungen und das ressourcenverwaltende Potenzial der Erholung während der Mittagspause und stärken damit die Validität und Nützlichkeit des adaptierten DSST zur Beurteilung der kognitiven Leistungsfähigkeit am Arbeitsplatz.

In der dritten empirischen Studie wollte ich die Praktikabilität und Nützlichkeit des 90-sekündigen SART für arbeitsbezogene Tagebuchstudien aufzeigen, indem ich den Zusammenhang zwischen psychologischen (Müdigkeit) und physiologischen (Herzfrequenzvariabilität; HRV) Erholungsprozessen am Abend und der kognitiven Leistungsfähigkeit zu Arbeitsbeginn am nächsten Morgen untersuchte. An drei Arbeitstagen trugen 65 Beschäftigte kontinuierlich einen Brustgurt mit Trockenelektroden und EKG-Sensoren zur Erfassung der HRV, beantworteten zwischen Arbeitsende und Schlafengehen stündliche Smartphone-Fragebögen und absolvierten am nächsten Morgen zu Beginn des Arbeitstages den adaptierten SART, wodurch Daten zu 200 Abenden und 185 Morgen gewonnen wurden. Latente Wachstumskurvenmodelle stützen die angenommenen U-förmigen psychologischen und physiologischen Erholungsverläufe am Abend. Darüber hinaus waren Verläufe der Müdigkeit mit einem längeren Rückgang vor einem zirkadianen Anstieg sowie Verläufe der HRV mit einem unmittelbareren Anstieg nach Arbeitsende positiv mit der kognitiven Leistungsfähigkeit am nächsten Morgen assoziiert. Diese Ergebnisse belegen den positiven Zusammenhang zwischen der psychophysiologischen Erholung am Abend und der kognitiven Leistungsfähigkeit zu Arbeitsbeginn und stützen damit die Validität und

Nützlichkeit des adaptierten SART zur Beurteilung der kognitiven Leistungsfähigkeit in arbeitsbezogenen Tagebuchstudien.

Insgesamt führt diese Dissertation den adaptierten DSST und SART als reliable, valide und praktikable Instrumente zur Beurteilung der momentanen kognitiven Leistungsfähigkeit als Näherungswert der Leistungsfähigkeit von Beschäftigten am Arbeitsplatz ein. Signifikante Zusammenhänge von Arbeitsanforderungen und Erholung mit der momentanen kognitiven Leistungsfähigkeit unterstreichen die Nützlichkeit der Tests in arbeitsbezogenen Tagebuchstudien. Daher können Forschende den kurzen, smartphone-basierten DSST und SART als geeignete Instrumente zur Messung objektiver verhaltensbezogener Leistungsindikatoren betrachten. Die kognitiven Leistungstests könnten besonders nützlich für Tagebuchstudien sein, die sich auf Stichproben konzentrieren, für die keine anderweitigen Verhaltensindikatoren der momentanen Arbeitsleistung vorliegen.

CHAPTER I: GENERAL INTRODUCTION

Job performance is a fundamental concept in industrial and organizational (I/O) psychology (J. P. Campbell, 2012; Sonnentag & Frese, 2012), which is multidimensional, comprising task performance (i.e., activities leading to observable work results) and contextual performance (i.e., activities benefiting the social and organizational work context; Sonnentag & Frese, 2012). Job performance is highly relevant for organizations' effectiveness (J. P. Campbell, 2012), as it contributes to the attainment of organizations' profit and nonprofit goals. To effectively manage job performance at work (Sonnentag & Frese, 2012), I/O psychology theories and research aim to identify its determinants.

As job performance is highly dynamic, fluctuating substantially across and within days (N. P. Podsakoff et al., 2019), investigating performance fluctuations in occupational diary studies (i.e., studies with repeated assessments at work; Bolger et al., 2003) alongside within-person predictors (e.g., work demands, recovery; Pindek et al., 2024; Steed et al., 2021) may provide key information for effective performance management (Sonnentag & Frese, 2012). However, despite their high relevance for employers, performance outcomes are largely underrepresented in organizational behavior (Pindek et al., 2019) and occupational health psychology research compared to health and well-being outcomes (Sonnentag et al., 2017; Steed et al., 2021). This is not surprising, as measuring momentary job performance is complex and comes with several challenges.

Job performance is often measured with subjective performance ratings (Pindek et al., 2024; Steed et al., 2021). However, self-reports may be biased, for example, due to social desirability in the case of positively connotated constructs (e.g., job performance; P. M. Podsakoff et al., 2024) or due to employees trying to avoid negative professional consequences when doubting anonymity in occupational diary studies. Additionally, I/O psychology research is repeatedly criticized for relying largely on self-report questionnaires (Sonnentag et al., 2017; Steed et al., 2021), as common method variance may lead to biased results (P. M. Podsakoff et al., 2024). Despite reducing the risk of common method bias (P. M. Podsakoff et al., 2024), subjective colleague or supervisor ratings may lack reliability and may be biased, for example, due to raters' implicit theories regarding specific work roles or due to raters lacking training (J. P. Campbell, 2012).

Although the necessity and benefits of objective performance measures have been debated for an extended period of time (J. P. Campbell, 2012), objective measurement of job performance is still highly challenging, particularly in white-collar work. High coding and matching efforts (e.g., for video recordings) make behavioral data use often very effortful and cost-intensive (P. M. Podsakoff et al., 2024). Furthermore, while blue-collar work (e.g., assembly line work) is typically linked to concrete products that can be compared to set performance standards (Hopp et al., 2009; Meijman & Mulder, 1998), performance in white-collar work (e.g., the quality of a medical treatment) is harder to quantify, particularly on day level (Hopp et al., 2009). White-collar tasks are more variable (e.g., treatment complexity of patients' illnesses may differ largely from case to case), which makes it harder to set uniform performance standards (Hopp et al., 2009). Furthermore, as white-collar tasks require intellectual and creative input, performance in these tasks is less easy to compare to set standards (Hopp et al., 2009). Additionally, white-collar workers' job performance is often only measurable after a certain time (e.g., after weeks or months; Hopp et al., 2009), which is not feasible for diary studies.

Momentary cognitive performance may be a viable alternative to job performance, particularly for professions that lack objective performance criteria (e.g., white-collar work; Hopp et al., 2009). Cognitive performance indicates cognitive functioning (Sliwinski et al., 2018), which is a proxy for employees' performance capacity (Meijman & Mulder, 1998). Cognitive functioning can be defined as those cognitive processes that are needed to acquire knowledge, to manipulate information, and to pursue reasoning (Kiely, 2023). Allowing employees to focus, store, recall, and process information, and to inhibit inappropriate responses or behaviors, cognitive functioning is essential for job performance in many work contexts (Ihle et al., 2015). Prior research has shown that cognitive functioning is significantly associated with critical subjective and objective occupational outcomes such as task performance (e.g., managerial performance), contextual performance (e.g., organizational citizenship behavior), and workplace safety (Dorrian et al., 2007; Higgins et al., 2007; J. E. Hunter, 1986; Lemonaki et al., 2021; Nye et al., 2022).

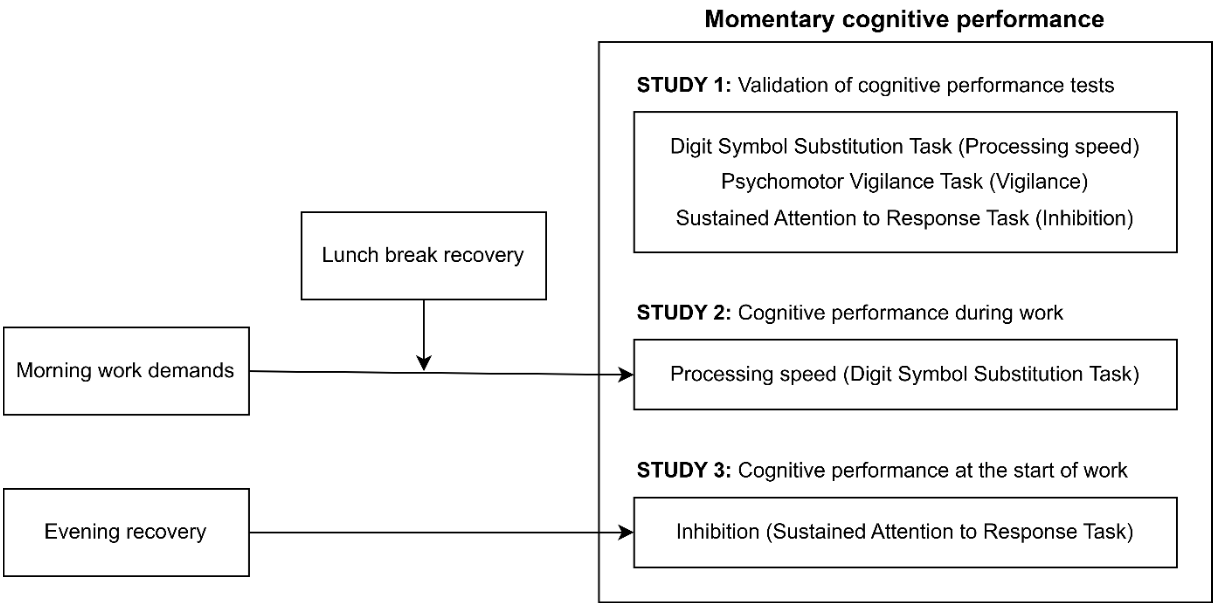
Similar to job performance, cognitive functioning is considered a fluctuating state that is affected by work situations (Meijman & Mulder, 1998; Sliwinski et al., 2018), for example, by work demands (G. G. Fisher et al., 2017), work schedules (e.g., shift work; Bufano et al., 2024), and break recovery (Riedl et al., 2023). Seminal occupational health psychology frameworks—such as the effort–recovery model (ERM; Meijman & Mulder, 1998) and the challenge–hindrance stressor framework (CHSF; Cavanaugh et al., 2000; M. A. LePine, 2022)—acknowledge cognitive functioning as a critical underlying mechanism in the relationship of work demands and recovery with job performance. Hence, a profound understanding of fluctuations of cognitive functioning at work and the impact of work demands and recovery on momentary cognitive functioning may help manage employees' job performance (M. A. LePine, 2022; Meijman & Mulder, 1998; Sonnentag & Frese, 2012).

Cognitive performance tests may objectively measure momentary cognitive functioning in everyday-life situations (Daniëls et al., 2020; Sliwinski et al., 2018; Verhagen et al., 2019). After being tied to laboratory settings for decades (e.g., due to the equipment needed), new technologies (e.g., smartphones) facilitate repeated objective assessments of cognitive functioning in everyday life (e.g., at work; Weizenbaum et al., 2020). However, the repeated use of established cognitive performance tests in diary studies—especially at work—requires short measurement durations to minimize participant burden, to ensure participant commitment over multiple days despite the repetitive study design, and to reduce the risk of distraction during task completion (Bolger et al., 2003; C. D. Fisher & To, 2012; Sliwinski et al., 2018). Hence, established cognitive performance tests—typically carried out once with long measurement durations in standardized laboratory settings (Sliwinski et al., 2018)—need to be shortened and validated for smartphone use in occupational diary studies.

Based on three diary studies, this dissertation aims to validate short smartphone-based cognitive performance tests, to evaluate their feasibility for assessing momentary cognitive functioning at work, and to demonstrate their utility for occupational diary studies. Study 1 lays the foundation of this dissertation by validating short smartphone-based versions of three established cognitive performance tests capturing cognitive functioning domains relevant for the work context. Study 2 and Study 3 present two exemplary applications of the most promising adapted cognitive performance tests in occupational diary studies. The two examples differ in the applied cognitive performance test, the assessment time of momentary cognitive functioning, and their focus on work demands and recovery. Figure 1.1 provides an overview of the conceptual framework of this dissertation, focusing on the assessment of momentary cognitive functioning.

Figure 1.1

Overall Conceptual Framework of This Dissertation



In the following, I will introduce the ERM (Meijman & Mulder, 1998) as the overarching theoretical framework of this dissertation, with a focus on cognitive functioning. Then, I will elaborate on cognitive functioning domains relevant at work. Subsequently, I will discuss the assessment of momentary cognitive functioning in occupational diary studies. Finally, I will conclude the first chapter with a short outline of this dissertation and its goals and contributions.

Cognitive Functioning in the Effort–Recovery Model

The ERM (Meijman & Mulder, 1998) builds the overarching theoretical framework of this dissertation. It posits cognitive functioning as a key component of employees' work potential, highlighting its critical role for job performance, health, and well-being at work. Furthermore, it identifies work demands and recovery as key predictors stimulating, depleting, and restoring employees' cognitive functioning. Overall, the ERM (Meijman & Mulder, 1998) explains under which conditions adaptive changes in cognitive functioning in response to mental and physical load can develop into severe negative (long-term) consequences for employee job performance, health, and well-being.

Work Potential and Cognitive Functioning

According to the ERM (Meijman & Mulder, 1998), cognitive functioning is a critical component of employees' work potential. An employee's work potential defines to what degree an employee is able and willing to invest effort in upcoming work tasks (Meijman & Mulder, 1998), thereby determining momentary job performance (Sonnentag & Frese, 2012). Meijman and Mulder (1998) define performance as the product or work result in comparison to pre-set standards and regulations.

Employees' work potential can be subdivided into computational and energetical processes (Meijman & Mulder, 1998). Computational processes comprise input, transformation, and storage of information (Meijman & Mulder, 1998), typical processes defining cognitive functioning (Kiely, 2023). In the following, I will therefore refer to computational processes as cognitive functioning. According to the ERM, cognitive functioning determines employees' capacity to perform at work, that is, whether they can successfully cope with upcoming tasks (Kiely, 2023; Meijman & Mulder, 1998).

Energetical processes can be interpreted as employees' willingness to perform, as they define the effort invested in work situations and the associated costs by managing cognitive functioning in accordance with employees' momentary psychophysiological states (Meijman & Mulder, 1998). Psychophysiological states can be subjectively perceived (e.g., fatigue) or manifest physiologically (e.g., HRV) or behaviorally (e.g., cognitive functioning; Meijman & Mulder, 1998). For example, if employees face a difficult task that requires high levels of cognitive functioning (e.g., high concentration) when they feel psychophysiologically strained, there may be a deviation between employees' current psychophysiological states and the required states to meet the task (e.g., cognitive functioning; Meijman & Mulder, 1998).

Acknowledging that employees interact proactively at work, the ERM (Meijman & Mulder, 1998) postulates that, depending on employees' individual work procedures, this deviation may either result in performance decrements or impaired employee well-being. Performance may primarily be negatively affected if employees experience high decision latitude (i.e., control in a specific work situation) and have the abilities and willingness to use it. In this case, employees may manage such deviations by sacrificing performance standards for the sake of less effortful processing strategies, manageable with reduced cognitive functioning (Meijman & Mulder, 1998). In contrast, well-being impairments are likely if employees (need to) stick to their initial performance standards and try to overcome the deviation of their actual psychophysiological state from the required psychophysiological state by investing additional compensatory effort (Meijman & Mulder, 1998). Compensatory effort creates functional load as employees mobilize additional cognitive resources to maintain or increase cognitive functioning for the sake of meeting performance standards, risking high physiological and behavioral costs and resource depletion (i.e., load effects; Hockey, 1997; Meijman & Mulder, 1998).

Work Demands and Cognitive Functioning

Hence, an employee's work potential (i.e., cognitive functioning, energy) defines if and at what costs employees can deal with upcoming work demands. Work demands can be defined as "those physical, social, or organizational aspects of the job that require sustained physical or mental effort and are therefore associated with certain physiological or psychological costs" (Demerouti et al., 2001, p. 501). The ERM (Meijman & Mulder, 1998) differentiates work demands into formal characteristics of the work situation on the one hand and environmental aspects and task demands on the other. While formal characteristics of the work situation (e.g., performance standards, break schedules) are considered rather stable work demands, task demands represent their situational, fluctuating manifestations (e.g., what has to be done within what time; Meijman & Mulder, 1998). As the focus of this dissertation is on within-person effects of work demands, in the following, the expression "work demands" refers to fluctuating task demands, while environmental aspects are not explicitly considered.

According to the ERM (Meijman & Mulder, 1998), work demands may also impact employees' work procedure, negatively affecting job performance or well-being if upcoming work demands (risk to) exceed employees' momentary work potential (i.e., energy and cognitive functioning). The ERM (Meijman & Mulder, 1998) distinguishes work demands mainly by their intensity. The CHSF (Cavanaugh et al., 2000; M. A. LePine, 2022)—another seminal occupational health psychology framework—differentiates work demands also by their type (challenge stressors vs. hindrance stressors). Additionally, the ERM (Meijman & Mulder, 1998) focuses on the duration of exposure to work demands. Both conceptual frameworks acknowledge that dealing with work demands can have positive and negative effects on job performance and well-being, drawing on underlying resource mechanisms (Cavanaugh et al., 2000; M. A. LePine, 2022; Meijman & Mulder, 1998).

Intensity of Work Demands and Cognitive Functioning. The ERM (Meijman & Mulder, 1998) postulates that the intensity of work demands can be positively associated with cognitive functioning. Cognitive functioning requires employees to mobilize cognitive resources (Ihle et al., 2015; Meijman & Mulder, 1998; D. C. Park, 2000; Young & Stanton, 2002). According to cognitive resource theories (e.g., Kahneman, 1973; Young & Stanton, 2002), individuals' cognitive resource pools are malleable, hence fluctuate in the short term depending on the mental demands they are facing. Cognitive resource pools can temporarily shrink in low-demand situations or temporarily grow in mentally demanding situations (Kahneman, 1973; Young & Stanton, 2002). In line with these cognitive resource theories, the ERM (Meijman & Mulder, 1998) postulates that the higher the intensity of work demands, the more cognitive resources are mobilized (up to a maximum threshold), stimulating cognitive functioning. However, Meijman and Mulder (1998) also acknowledge that highly intense work demands exceeding employees' work potential can be associated with severe load effects due to required compensatory effort.

Type of Work Demands and Cognitive Functioning. According to the CHSF (Cavanaugh et al., 2000), the positive associations between work demand intensity and cognitive functioning are not uniformly applicable across all types of work demands. The CHSF (Cavanaugh et al., 2000) differentiates challenge and hindrance stressors. Challenge stressors are work demands that facilitate goal attainment and personal growth (e.g., mental demands; Cavanaugh et al., 2000; M. A. LePine, 2022). In contrast, hindrance stressors are work demands that interfere with goal attainment (e.g., interpersonal conflicts; Cavanaugh et al., 2000; M. A. LePine, 2022). Both stressor types affect employees' work potential, but in opposing ways.

According to the CHSF (M. A. LePine, 2022), challenge stressors are linked to increased engagement, that is, increased energy levels. In turn, stimulated energy levels—indicating the willingness to perform according to the ERM (Meijman & Mulder, 1998)—should mobilize more cognitive resources. As cognitive functioning depends on cognitive resources (Young & Stanton, 2002), challenge stressors should enhance employees' work potential, that is, energy and cognitive functioning (Meijman & Mulder, 1998).

In contrast, hindrance stressors provoke negative affect (e.g., frustration, anger) and disengagement, taxing employees' resources and being associated with reduced energy (M. A. LePine, 2022). Indicating reduced willingness to perform, reduced energy may be linked to shrinking cognitive resource pools (Meijman & Mulder, 1998; Young & Stanton, 2002). Hence, hindrance stressors may be associated with reduced energy and cognitive functioning, impairing employees' work potential (Meijman & Mulder, 1998).

Duration of Exposure to Work Demands and Cognitive Functioning. However, the ERM (Meijman & Mulder, 1998) postulates that—independent of their intensity and type—the repeated and sustained exposure to work demands may be linked to severe load effects. Generally, dealing with work demands requires mental and physical effort and therefore strains employees' resources and psychophysiological states (M. A. LePine, 2022; Meijman & Mulder, 1998). Hence, the longer employees are exposed to work demands, the higher the mental and physical load impeding employees' work potential (Meijman & Mulder, 1998).

Conflicts between upcoming work demands and required work potential (i.e., cognitive functioning, energy) typically arise in moments of mental fatigue (Meijman & Mulder, 1998). Mental fatigue is defined as the "decline in the ability and efficiency of mental activities that is caused by excessive mental activities" (Ishii et al., 2014, p. 469). According to cognitive resource theories (e.g., Young & Stanton, 2002), the repeated and sustained exposure to mental demands exceeding the declining cognitive resource capacity may result in reduced cognitive functioning. Hence, mental fatigue can be interpreted as a consequence of expending mental effort and typically arises during or after extended work periods (Kato et al., 2009). Mental fatigue temporarily impairs cognitive functioning (e.g., reduced attention or cognitive control; Kato et al., 2009), thereby reducing employees' momentary performance capacity (Meijman & Mulder, 1998).

Meijman and Mulder (1998) acknowledge that initial resource-mobilizing effects of work demands may shift into load reactions (e.g., feeling tense) when work demands exceed employees' work potential (e.g., due to mental fatigue). Hence, even challenge stressors (e.g., mental demands)—that may initially be associated with resource mobilization and increased cognitive functioning (M. A. LePine, 2022; Young & Stanton, 2002)—may be linked to delayed decreases in energy and cognitive functioning due to resource depletion and psychophysiological strain (M. A. LePine, 2022; Meijman & Mulder, 1998).

Recovery and Cognitive Functioning

According to the ERM (Meijman & Mulder, 1998), recovery may prevent adaptive short-term load effects (e.g., mental fatigue) from leading into a vicious cycle of accumulating negative load effects and long-term health consequences (e.g., permanent cognitive impairment). Recovery is a process of "the restoration of strained resources" (Sonnentag & Geurts, 2009, p. 27) and "psychophysiological unwinding that is the opposite of the activation of psychophysiological systems during effort expenditure" (Geurts & Sonnentag, 2006, p. 483). Hence, recovery can be considered the antagonist of the aforementioned mental and physical load effects (Meijman & Mulder, 1998). Equally being linked to changing psychophysiological states, recovery can reflect in psychological (e.g., reduced fatigue), behavioral (e.g., increased cognitive functioning), and physiological outcomes (e.g., reduced HRV; Sonnentag & Geurts, 2009). Both previous load effects and insufficient recovery can provoke an imbalance between work demands and work potential that may result in performance decrements or well-being impairments (Meijman & Mulder, 1998).

Based on the occupational health psychology literature, recovery can be considered both as a predictor of cognitive functioning and as a moderator of the relationship between work demands and cognitive functioning (Meijman & Mulder, 1998; Sonnentag & Fritz, 2015). By replenishing strained resources and psychophysiological states, recovery restores and maintains employees' work potential (i.e., cognitive functioning and energy; Meijman & Mulder, 1998; Sonnentag & Geurts, 2009). Thereby, recovery prevents and counteracts conflicts between work demands and employees' work potential, ensuring job performance and well-being at work (Meijman & Mulder, 1998). Typical recovery periods interrupting sustained and repeated exposure to work demands are the lunch break and the evening after work (Sonnentag & Geurts, 2009).

Lunch Break Recovery and Cognitive Functioning. Due to lunch breaks interrupting sustained exposure to work demands during the workday, lunch break recovery may be considered a moderator of the associations between work demands and cognitive functioning at work (Sonnentag & Fritz, 2015). Being defined as a "continuous process of harmonizing the 'actual state' with the state that is 'required' at that moment" (Zijlstra et al., 2014, p. 244), recovery during lunch breaks may counteract conflicts between employees' work potential (i.e., energy and cognitive functioning) and upcoming work demands after the lunch break. By restoring resources and psychophysiological states, lunch break recovery manages the balance between work potential and work demands, preventing the need for compensatory effort. Therefore, lunch break recovery may buffer the accumulating depleting effects of sustained exposure to work demands and potentially even maintain the resource-mobilizing effects of challenge stressors over longer work periods (M. A. LePine, 2022; Meijman & Mulder, 1998; Sonnentag & Geurts, 2009).

Evening Recovery and Cognitive Functioning. As the evening after work interrupts the repeated exposure to work demands over consecutive workdays, evening recovery can be considered a predictor of employees' work potential at the start of work the next morning, that is, next-morning cognitive functioning and energy (Sonnentag & Fritz, 2015). According to the ERM (Meijman & Mulder, 1998), evening recovery is quantitatively and qualitatively sufficient if psychophysiological states return to baseline levels (i.e., states in a situation without stressor confrontation), which means that employees can start their next workday without any residual load effects that may impede their work potential. In contrast, if recovery in between consecutive work periods is insufficient, load effects persist and employees return to work in a suboptimal psychophysiological state (e.g., mentally fatigued; Meijman & Mulder, 1998). The combination of sustained load effects and the need for compensatory effort may result in reduced cognitive functioning, job performance, and well-being (Meijman & Mulder, 1998).

Overall, according to the ERM (Meijman & Mulder, 1998), effort and recovery cycles determine if and at what costs employees can deal with work demands and therefore affect job performance and well-being. Cognitive functioning can be considered a critical underlying factor of associations of work demands and recovery with job performance and well-being (Meijman & Mulder, 1998). Determining if and at what costs employees can deal with upcoming work demands—which is decisive for job performance and well-being—cognitive functioning can be considered a proxy of employees' performance capacity. Associations of work demands and recovery with momentary cognitive functioning may provide useful evidence for effectively managing employees' job performance at work.

Cognitive Functioning Domains Relevant at Work

Cognitive functioning can be subdivided into domains such as attention (e.g., vigilance, alertness), memory (e.g., working memory, episodic memory), and executive functioning (e.g., inhibition, planning; Irwin et al., 2020; Lezak et al., 2004; Schmidt et al., 2007). Although focusing mostly on the cognitive functioning domains of memory (e.g., long-term memory, working memory) and information processing, the ERM acknowledges the relevance of "those adaptive systems that play a role in the mental functioning or the information processing in a broad sense" (Meijman & Mulder, 1998, p. 12). Therefore, I opted for an empirical approach to identify those cognitive functioning domains relevant for occupational functioning (Cambridge et al., 2018), aiming to select suitable cognitive performance tests to measure employees' cognitive functioning at work. In line with the recommendation of Shields (2020), I reviewed the literature to identify those cognitive functioning domains sensitive to load effects and relevant for job performance (Meijman & Mulder, 1998).

I identified memory (particularly working memory), attention (particularly sustained attention), and executive functioning (particularly inhibition) as cognitive functioning domains sensitive to load effects (e.g., mental load, burnout). In a systematic review comprising 15 original articles (consisting of cross-sectional, longitudinal, and intervention studies), burnout was significantly associated with memory, attention, and executive functioning (Deligkaris et al., 2014). Additionally, Lemonaki et al. (2021) found a negative longitudinal relationship between burnout and working memory and inhibition. Also, in experimental settings, mental load was associated with decrements in sustained attention and inhibition (Kato et al., 2009; Steinborn et al., 2010).

Furthermore, visual processing and processing speed, as well as memory (particularly working memory), attention, and executive functioning appear to be closely related to job performance. For example, a systematic review found significant cross-sectional relationships of verbal memory, attention, and executive functioning with occupational functioning (Cambridge et al., 2018). The findings of Shibaoka et al. (2023) suggest that working memory, attention, and executive functioning performance can differentiate employees with high self-reported job performance in diverse occupational fields from those with low self-reported job performance. Also, Lemonaki et al. (2021) found a significant cross-sectional association between working memory performance and self- and colleague-reported task performance, with working memory performance mediating the negative association between burnout and task performance. Beyond that, a meta-analysis of cross-sectional and longitudinal studies identified visual processing and processing speed as the strongest cognitive functioning correlates with subjective and objective task performance, training performance, and organizational citizenship behavior after considering general cognitive ability (Nye et al., 2022).

Based on this literature review, I considered visual processing, processing speed, working memory, sustained attention, and inhibition as highly relevant cognitive functioning domains potentially underlying the associations of work demands, recovery, and job performance as postulated by the ERM (Meijman & Mulder, 1998). Visual processing comprises the creation, storage, retrieval, and manipulation of impressions and sensations (McGrew, 2009). At work, visual processing is necessary, for example, to read e-mails, to interpret charts or maps, to drive, or to arrange decorations. Processing speed can be defined as the speed at which individuals can process information (i.e., perform elementary cognitive operations; Mashburn et al., 2024). It is required for many tasks and therefore the strongest indicator of overall cognitive functioning (P. D. Harvey, 2019). At work, processing speed is particularly relevant for tasks (both simple and complex) that need to be completed quickly (e.g., under time pressure; P. D. Harvey, 2019). Working memory can be defined as the extent of momentary cognitive resources available for information processing (D. C. Park, 2000). At work, it allows employees to consciously hold, process, and use verbal and nonverbal information to complete a certain task (P. D. Harvey, 2019).

Attention refers to processes that improve information processing (Schmidt et al., 2007) and can be divided into the two subdomains of selective attention and sustained attention (i.e., vigilance; P. D. Harvey, 2019). Selective attention allows employees to focus on relevant information and ignore nonrelevant information (P. D. Harvey, 2019). Sustained attention allows employees to stay focused over time and covers concentration (P. D. Harvey, 2019). At work, attention allows employees to concentrate and focus on one task and to avoid errors and distractions.

Executive functioning allows for higher-order cognitive processes (e.g., reasoning, problem solving) by controlling the other cognitive functioning domains (P. D. Harvey, 2019). Inhibition is a subdomain of executive functioning (P. D. Harvey, 2019). Inhibition refers to intentional control over cognitive sub-processes (Miyake et al., 2000; Oosterholt et al., 2012). At work, inhibition allows employees to suppress inappropriate impulsive, automatic, or prepotent reactions (i.e., in conflict situations with colleagues or customers; Miyake et al., 2000). Overall, due to their sensitivity to load effects and their relevance for job performance, capturing momentary fluctuations of these cognitive functioning domains at work may provide valuable information for effective job performance management.

Measuring Cognitive Functioning in Occupational Diary Studies

Cognitive functioning is often unconscious and can therefore not easily be captured with employee self-reports (Meijman & Mulder, 1998). Instead, changes in momentary cognitive functioning can be measured with cognitive performance tests (Schmidt et al., 2007; Sliwinski et al., 2018). Typically, load effects (e.g., mental fatigue) are linked to increasing error rates, reaction times, or variability of reaction times in cognitive performance tests (Kato et al., 2009; Steinborn et al., 2010).

To detect these load effects with cognitive performance tests, the ERM (Meijman & Mulder, 1998) recommends focusing on mental efficiency, that is the ratio between performance and associated effort (Meijman & Mulder, 1998). In contrast to task effectiveness, which focuses only on achieved output targets (e.g., number of errors), task efficiency considers the costs linked to primary test performance (Hockey, 1997). Although mentally fatigued employees may succeed in maintaining primary performance outcomes (e.g., the number of errors), decrements in secondary performance outcomes (e.g., slower reaction times) are quite common (Hockey, 1997). Hence, decrements in mental efficiency (i.e., the ratio of correct responses and reaction time) can detect reduced cognitive functioning resulting from increased mental load (Hockey, 1997; Meijman & Mulder, 1998). As cognitive functioning is considered a critical component of employees' work potential, momentary mental efficiency in a cognitive performance test can indicate if and at what costs employees can deal with work demands in this particular situation (Meijman & Mulder, 1998).

Cognitive Performance Tests

Aiming to cover the aforementioned relevant cognitive functioning domains, this dissertation focuses on three cognitive performance tests: the Digit Symbol Substitution Task (DSST), the Psychomotor Vigilance Task (PVT), and the Sustained Attention to Response Task (SART). The DSST (Wechsler, 1939) is a matching task that can be considered a typical task assessing working memory, visual processing, and information processing speed (Royer et al., 1981; Verhagen et al., 2019). The PVT (Dinges & Powell, 1985; Doran et al., 2001) is a reaction time task that is typically used to measure attention, particularly sustained attention (Irwin et al., 2020; Schmidt et al., 2007). The SART (Robertson et al., 1997) is a Go–NoGo task that can be applied to measure executive functioning, in particular inhibition (Irwin et al., 2020; Manly et al., 2002; Schmidt et al., 2007). All three cognitive performance tests record the number of correct responses, errors, and reaction times; hence, they allow for the evaluation of mental efficiency.

Cognitive Performance Tests in Diary Studies

To examine momentary cognitive functioning at work, employees need to complete the same cognitive performance test repeatedly in different everyday work situations (usually multiple times per day; Trull & Ebner-Priemer, 2013). Diary studies allow for a situational perspective when investigating load and recovery effects, for example, within one workday and between successive workdays, focusing on within-person instead of between-person differences (Bolger et al., 2003). Due to aligning with the episodic assumptions of underlying conceptual frameworks (e.g., ERM, CHSF), diary studies are the gold standard for investigating short-term effects of work demands and recovery on cognitive functioning (Ganster & Rosen, 2013; Pindek et al., 2024; Sonnentag et al., 2017). To investigate within-person associations of work demands and recovery with momentary cognitive functioning, the repeated cognitive performance tests need to be combined with self-reported experiences (Bolger et al., 2003).

New technologies, such as smartphones, allow for a feasible combination of self-reports with cognitive performance tests. For example, Sliwinski et al. (2018) demonstrated the feasibility of smartphone-based cognitive performance tests for diary studies. However, to minimize the participant burden linked to the repeated assessments in everyday life, the challenge is to keep the assessments short (Bolger et al., 2003; C. D. Fisher & To, 2012; Sliwinski et al., 2018). In diary studies with more than five daily questionnaires or study periods spanning more than one week, one assessment should not exceed three minutes (Hektner et al., 2007).

Following these recommendations and aiming for feasibility, the aforementioned cognitive performance tests (DSST, PVT, SART)—typically presented once with long measurement durations in the laboratory—need to be shortened and validated for smartphone use to be effectively applied in occupational diary studies. Optimally, the assessment duration of the cognitive performance tests should be reduced to measurement durations shorter than three minutes to be feasible for the combined assessment with self-reports multiple times per day (Hektner et al., 2007).

Dissertation Outline and Overview of Empirical Studies

To adapt the established cognitive performance tests to short smartphone-based versions and to demonstrate their feasibility and usefulness for repeated assessments in occupational diary studies investigating the associations of work demands and recovery with cognitive functioning (as postulated by the ERM and the CHSF; M. A. LePine, 2022; Meijman & Mulder, 1998), I conducted three empirical studies. The first study (Study 1) lays the methodological foundation for this dissertation, validating short smartphone-based versions of the three cognitive performance tests and exploring their sensitivity to fluctuating work demands and recovery in a student sample. The latter two studies represent applications of the adapted cognitive performance tests in occupational diary studies investigating momentary cognitive functioning in the context of fluctuating work demands and recovery within one workday (Study 2) and load and recovery effects between two consecutive workdays (Study 3).

In the second chapter of this dissertation, I present Study 1, which focuses on the validation of short smartphone-based cognitive performance tests for use in occupational diary studies. With this empirical study, I laid the methodological foundation for the following studies by identifying the minimum measurement duration of three established cognitive performance tests providing reliable indicators of within-person change in cognitive functioning. Furthermore, I tested whether the shortened smartphone-based cognitive performance tests produce valid indicators of cognitive functioning and are sensitive to load and recovery effects. To answer the research questions, over 14 days, 46 university students completed three-minute versions of the three cognitive performance tests separately once per day, coupled with short self-report questionnaires on smartphones at semi-random times (separated by at least two hours), generating 559–575 situational assessments per cognitive performance test. The results being most convincing lead to the application of the 90-second DSST and SART in occupational diary studies in Study 2 (DSST) and Study 3 (SART).

In the third chapter of this dissertation, I present Study 2, which captures associations of morning challenge and hindrance stressors with cognitive functioning at three times at work (before the lunch break, after the lunch break, and at the end of work), considering lunch break recovery as a moderator. Based on the CHSF (Cavanaugh et al., 2000; M. A. LePine, 2022), I assumed that challenge stressors are positively and hindrance stressors are negatively associated with cognitive performance. Based on the ERM (Meijman & Mulder,

1998) and due to managing the balance between work demands and work potential (Zijlstra et al., 2014), I hypothesized that lunch break recovery moderates lagged associations of morning work demands with afternoon cognitive functioning (after the lunch break and at the end of the workday) by buffering depleting effects of morning work demands in general and by prolonging stimulating effects of challenge stressors in particular. To test these hypotheses, 63 knowledge workers answered questionnaires and completed the DSST on smartphones three times a day over two work weeks, providing 443 assessments before the lunch break, 414 after the lunch break, and 426 at the end of the workday.

In the fourth chapter of this dissertation, I present Study 3, in which I investigated psychological (fatigue) and physiological (heart rate variability; HRV) evening recovery trajectories and their effects on next-morning energy and cognitive functioning. Based on the ERM (Meijman & Mulder, 1998) and the allostatic load model (ALM; McEwen, 1998), and considering previous research on circadian influences (Coumel et al., 1994; Hülsheger, 2016), I assumed U-shaped psychophysiological trajectories between the end of work and bedtime. Based on the ERM (Meijman & Mulder, 1998) and the ALM (McEwen, 1998), I further hypothesized that a more complete psychological (i.e., a fatigue trajectory with a later and lower minimum) and a more immediate physiological evening recovery trajectory (i.e., an HRV trajectory with an earlier and higher minimum) promote next-morning energy and cognitive functioning. To test these hypotheses, 65 employees answered hourly questionnaires between the end of work and bedtime over three evenings, wore chest belts with ECG sensors to extract HRV throughout 72 hours, and completed questionnaires and the SART on smartphones the next morning at the start of work, providing data on 200 evenings and 185 mornings.

Each of the empirical studies presented in Chapter II (Study 1), Chapter III (Study 2), and Chapter IV (Study 3) comprises an individual Introduction, Theoretical Background, Method, Results, and Discussion section and can be read and interpreted independently. In the fifth concluding chapter (General Discussion), I summarize the results of the three empirical studies and integrate these findings into a bigger picture. In particular, I derive implications for research, theory, and practice; discuss this dissertation's strengths and limitations; and provide directions for future research.

Goals and Contributions of This Dissertation

This dissertation contributes to the research fields of I/O psychology—in particular occupational health psychology and organizational behavior—and cognitive psychology. Its goals and contributions can be grouped into two overarching themes. First, this dissertation aims to advance the two aforementioned research fields by adapting cognitive performance tests established in cognitive psychology for use in occupational diary studies and to evaluate their feasibility and utility in this application context. Second, this dissertation aims to contribute to the ERM (Meijman & Mulder, 1998) and the CHSF (M. A. LePine, 2022), as well as to the recovery and cognitive psychology literature, by measuring momentary cognitive functioning at work as a proxy of employees' performance capacity in the context of work demands and recovery in two exemplary occupational diary studies.

Providing Cognitive Performance Tests for Use in Occupational Diary Studies

The first overarching theme focuses on the methodological goals of this dissertation. It addresses the added value of providing and evaluating adapted cognitive performance tests to measure momentary cognitive functioning as a proxy of employees' performance capacity.

By providing three short, smartphone-based cognitive performance tests capturing cognitive functioning dimensions relevant for job performance and load effects with suggestions for their feasible and effective application, this dissertation aims to reduce the hurdles of combining self-reports with objective behavioral assessments in occupational diary studies. Thereby, this dissertation follows the repeated call for objective behavioral outcomes in occupational field studies (G. G. Fisher et al., 2017; Sonnentag et al., 2017; Steed et al., 2021). By validating the cognitive performance tests for short measurement durations and smartphone use, this dissertation aims to increase their feasibility for occupational diary studies. The short measurement durations facilitate repeated assessments by ensuring participant motivation and reducing risks of distractions (Bolger et al., 2003; C. D. Fisher & To, 2012; Sliwinski et al., 2018). Presenting cognitive performance tests on smartphones enables behavioral assessments in diverse work settings beyond professions with access to a PC. Additionally, by providing the code for the software, this dissertation aims to make the cognitive performance tests accessible and easily applicable for researchers.

By applying the two most promising cognitive performance tests in occupational diary studies (Study 2, Study 3), this dissertation aims to demonstrate their feasibility for occupational diary studies. By investigating associations of work demands and recovery with cognitive functioning at work, this dissertation aims to highlight the sensitivity of cognitive performance tests to fluctuations in work demands and recovery and their utility for examining load and recovery effects at work.

These methodological goals are linked to three key contributions to the research field. By measuring momentary cognitive functioning at work, short smartphone-based cognitive performance tests (1) provide sensitive and broad indicators of employee performance capacity, especially in occupational groups that lack objective performance indicators, (2) can depict unconscious phenomena underlying employee perceptions, and (3) capture objective behavioral outcomes of work demands and recovery effects.

Cognitive Functioning as an Indicator of Employee Performance Capacity. Cognitive functioning can be considered a broad objective indicator of overall performance capacity relevant for multiple job performance dimensions (e.g., task performance, organizational citizenship behavior; Nye et al., 2022), which is feasible for professions lacking objective performance criteria (e.g., white-collar work; Hopp et al., 2009) and considers the costs linked to performance (Meijman & Mulder, 1998). In contrast, observable behavioral performance indicators (e.g., number of produced pieces per shift) may only provide information on one performance aspect (e.g., task performance), often neglecting the multi-faceted nature of job performance (Rotundo, 2002). Focusing on selected primary performance outcomes risks potentially overlooking performance decrements in secondary performance outcomes indicating compensatory effort (Hockey, 1997; Sonnentag & Geurts, 2009). Conversely, mental efficiency measured with cognitive performance tests is highly sensitive to load effects and detects the costs associated with performance (Hockey, 1997; Meijman & Mulder, 1998).

Capturing compensatory effort, mental efficiency can be considered a proximate and highly sensitive indicator of load effects (Meijman & Mulder, 1998; Sonnentag & Geurts, 2009). Therefore, deviations in cognitive functioning at work may serve as early warning signs of reduced work potential before performance decrements in job performance arise (Meijman & Mulder, 1998; Sonnentag & Geurts, 2009). Due to its sensitivity to deviations in performance and associated effort (Meijman & Mulder, 1998), mental efficiency may unveil a lack of recovery before it can be perceived or observed (Sonnentag & Geurts, 2009). By detecting the load process at its root (Lemonaki et al., 2021; Meijman & Mulder, 1998; Sonnentag & Geurts, 2009), cognitive performance tests enable early prevention, avoiding compensatory effort, hence maintaining job performance, health, and well-being.

Cognitive Functioning as an Unconscious Phenomenon. By providing cognitive performance tests to capture cognitive functioning in everyday work contexts (Verhagen et al., 2019), this dissertation contributes to the understanding of unconscious phenomena underlying job performance fluctuations at work. Cognitive functioning is often unconscious; hence, it can barely be assessed with self-report questionnaires (Hockey, 1997; Meijman & Mulder, 1998). For example, previous research found only a low correspondence between self-reported and objectively measured cognitive functioning (e.g., executive functioning, attention; Diener et al., 2016). Hence, cognitive performance tests may shed light on fundamental unconscious mechanisms underlying employee perceptions, such as cognitive resource dynamics (M. A. LePine, 2022; Sonnentag et al., 2017). Although cognitive resources are frequently discussed in the literature as the underlying mechanism of observable psychological processes (e.g., M. A. LePine, 2022; Meijman & Mulder, 1998), they were rarely empirically examined. The main reason for this lack of research may be that cognitive resources are difficult to measure using conventional research methods (Hommel & Dreisbach, 2022). Due to cognitive functioning depending on limited cognitive resources (Ihle et al., 2015; Park, 2000; Young & Stanton, 2002), cognitive performance tests may reduce these methodological hurdles by providing objective indicators of cognitive resource pools (Young & Stanton, 2002).

Cognitive Functioning as an Objective Behavioral Indicator. Providing objective cognitive performance tests as a feasible alternative to self-reports of cognitive functioning or work potential, this dissertation contributes to the field by initiating a shift from a strong focus on self-report outcomes in I/O psychology to more diverse methodological approaches aiming for more robust findings (Sonnentag et al., 2017; Steed et al., 2021). While self-reports themselves may be biased, for example, due to social desirability (P. M. Podsakoff et al., 2024), faking good is hardly possible in objective cognitive performance tests, particularly when mental efficiency scores are used (e.g., considering primary and secondary performance outcomes). Furthermore, the combined assessment of self-reported experiences and objective cognitive functioning is an effective way to reduce the risk of common method bias (P. M. Podsakoff et al., 2024), offering a feasible way for more robust research results.

Additionally, this dissertation contributes to the field by making the assessment of currently underrepresented behavioral data more feasible and attractive for I/O psychology researchers (G. G. Fisher et al., 2017; Sonnentag et al., 2017; Steed et al., 2021). Being measured through employees' performance demonstrated in cognitive performance tests, cognitive functioning can be considered a behavioral indicator (Sonnentag & Geurts, 2009).

Smartphone-based cognitive performance tests can be presented on the same medium as self-reports, which makes behavioral data easily accessible and minimizes matching efforts.

Contributing to the Literature on Work Demands, Recovery, and Cognitive Functioning

The second overarching theme focuses on goals linked to the exemplary application of short smartphone-based cognitive performance tests in the context of fluctuating work demands and recovery in occupational diary studies. With the overall goal to contribute to the literature, this dissertation tests theoretical assumptions of seminal conceptual frameworks—the ERM (Meijman & Mulder, 1998) and the CHSF (Cavanaugh et al., 2000; M. A. LePine, 2022)—with cognitive functioning as a substantive and sensitive indicator of load and recovery effects (Sonnentag & Geurts, 2009; Sonnentag et al., 2017). By measuring momentary cognitive functioning at work, this dissertation aims to provide insights on (1) the associations between work demands and cognitive functioning, considering underlying cognitive resource dynamics, (2) the role of recovery effects linked to lunch breaks and the evening after work for cognitive functioning at work, and (3) fluctuations of momentary cognitive functioning in real-life situations in general.

Work Demands and Resource Dynamics at Work. First, by applying time-lagged designs (Study 2, Study 3) and considering the interplay of work demands and recovery (Study 2), this dissertation aims to provide insights into sustained load effects throughout the workday and their underlying resource dynamics, thereby testing and advancing the ERM (Meijman & Mulder, 1998) and the CHSF (Cavanaugh et al., 2000; M. A. LePine, 2022). By applying a temporal approach focusing on both immediate and sustained effects of challenge and hindrance stressors (Study 2), this dissertation provides comprehensive insights into the effects of work demands on cognitive functioning depending on their intensity and type and the general duration of sustained work demand exposure (M. A. LePine, 2022; Meijman & Mulder, 1998). Thereby, this dissertation enriches previous, mainly cross-sectional research on the association between work demands and performance, focusing mostly on the intensity and type of work demands (Pindek et al., 2024). Empirical evidence on lagged associations of challenge or hindrance stressors with cognitive functioning enhances our understanding of the persistence of load effects at work, testing the assumptions of the ERM (Meijman & Mulder, 1998) and contributing to the CHSF (M. A. LePine, 2022).

Furthermore, considering cognitive functioning (i.e., an indicator of cognitive resources; Young & Stanton, 2002) as an outcome and lunch break recovery (i.e., a period of resource restoration interrupting sustained exposure to work demands; Meijman & Mulder, 1998) as a moderator (Study 2) in the context of work demands, this dissertation contributes to the understanding of the dynamic interplay of resource mobilization, depletion, and restoration at work. Despite being considered part of the core explanatory mechanisms of associations of work demands and recovery with employee well-being and performance in the ERM (Meijman & Mulder, 1998) and the CHSF (M. A. LePine, 2022), cognitive resource dynamics have rarely been examined in empirical studies (for an exception, see Lemonaki et al., 2021), particularly on the day level. By measuring momentary cognitive functioning at work, this dissertation takes a first step towards unveiling “the ‘black box’ of resource dynamics” (M. A. LePine, 2022, p. 245) in the CHSF. Furthermore, by identifying lunch break recovery as a critical boundary condition of resource-mobilizing effects of challenge stressors, this dissertation highlights break recovery as a critical tackling point for effective management of employee resources at work, preventing load effects and maintaining job performance, health, and well-being (Meijman & Mulder, 1998; Sonnentag & Geurts, 2009).

Various Perspectives on Recovery. Second, this dissertation aims to add multifaceted insights to the body of research on recovery by operationalizing recovery as a process, considering different recovery indicators (i.e., psychological, physiological, and behavioral) and recovery periods (i.e., lunch break, evening after work), and examining recovery both as a predictor of cognitive functioning and as a moderator of the relationship between work demands and cognitive functioning. By investigating psychological and physiological recovery processes (Study 3), this dissertation aims to test the multidimensional and dynamic nature of recovery often ignored in recovery research.

By investigating evening recovery trajectories (Study 3), this dissertation provides a dynamic perspective on recovery, contributing to the understanding of how recovery unfolds after the end of work and which temporal characteristics of the trajectory benefit next-morning employee performance capacity (Sonnentag et al., 2017). This methodological approach lives up to the definition of recovery as a process (Geurts & Sonnentag, 2006; Meijman & Mulder, 1998; Zijlstra et al., 2014), which is rarely taken into account empirically. The insights gained by this approach may allow for optimal scheduling of intervention measures to effectively counteract load effects and maintain employees' work potential (e.g., immediately after work).

Furthermore, by replicating previous findings on associations between recovery and employee perceptions with physiological recovery processes (Study 3) and cognitive functioning as a substantive behavioral recovery outcome (Study 2, Study 3), this dissertation contributes to the robustness of previous recovery research, which is highly dominated by self-reported psychological recovery indicators (Sonnentag & Geurts, 2009; Sonnentag et al., 2017). Furthermore, it advances the multidimensional understanding of recovery (Sonnentag & Geurts, 2009).

Additionally, by examining lunch break recovery as a moderator of work demands–cognitive functioning associations (Study 2) and evening recovery as a predictor of next-morning cognitive functioning (Study 3), this dissertation aims to provide a comprehensive understanding of the critical role of recovery for counteracting work-related load effects. By investigating associations of lunch break recovery at work (Study 2) and evening recovery after work (Study 3) with cognitive functioning, this dissertation provides insights regarding critical recovery periods that manage employees' work potential and interrupt accumulating load effects (Meijman & Mulder, 1998). Findings on two recovery periods that are closely intertwined with work periods allow for the derivation of highly effective interventions interrupting load effects (Meijman & Mulder, 1998).

By considering the predicting (Study 3) and moderating (Study 2) role of recovery for cognitive functioning at work, this dissertation demonstrates the dual meaning of recovery for managing deviations between work demands and work potential at work and for restoring employees' work potential after work (Geurts & Sonnentag, 2006; Meijman & Mulder, 1998; Zijlstra et al., 2014). Although key theoretical frameworks recognize recovery as both a predictor and a moderator (Meijman & Mulder, 1998; Sonnentag & Fritz, 2015), the moderating role of recovery is rarely empirically tested (for an exception, see Sonnentag et al., 2010). However, the moderating role of recovery could be particularly critical in mitigating load effects linked to work demands for the sake of maintaining employees' performance and well-being throughout periods of sustained exposure to work demands (e.g., throughout the workday).

Momentary Cognitive Functioning at Work. Third, by applying adapted versions of cognitive performance tests in diary studies (Study 1, Study 2, Study 3), this dissertation aims to provide ecologically valid insights into momentary cognitive functioning in everyday (work) situations. Thereby, this dissertation enriches the cognitive psychology literature, which typically focuses on maximum cognitive functioning in standardized experimental laboratory settings (Sliwinski et al., 2018). By providing ecologically valid insights into typical cognitive functioning in everyday (work) contexts (Trull & Ebner-Priemer, 2013; Verhagen et al., 2019), this dissertation adds empirical evidence to the small body of research on momentary cognitive functioning in real-life occupational contexts (for exceptions, see Baethge & Rigotti, 2015; El Mansouri et al., 2024).

CHAPTER II: VALIDATION OF THE COGNITIVE PERFORMANCE TESTS

Study 1: "Measuring Situational Cognitive Performance in the Wild: A Psychometric Evaluation of Three Brief Smartphone-Based Test Procedures"[1]

Summary

Mobile devices provide new opportunities to draw conclusions about cognitive performance in everyday situations. To gain insights into cognitive performance patterns in healthy adult populations, we adapted three established cognitive tests for smartphone use: the Digit Symbol Substitution Task (DSST), Sustained Attention to Response Task (SART), and Psychomotor Vigilance Task (PVT). To increase their feasibility for ambulatory assessment, we identified the minimum measurement durations that provide reliable and valid state measures of cognitive performance. Over 2 weeks, 46 participants performed each test once per day at random times, along with self-reports (e.g., on concentration, mood, and mental demands). The validity and reliability of change are promising for the 30-second PVT and 90-second DSST and SART. The DSST and SART provide fruitful outcomes for ambulatory field studies linked to mood, stress, and mental demands. We provide digital versions of the adapted DSST and SART online for free.

[1] Study 1 is the accepted post-review and pre-production version of the original manuscript by Perzl, Riedl, & Thomas (2023) published open access (CC BY 4.0) in Assessment. © 2023, Sage Journals.
Chapter II is identical to the accepted manuscript.
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Introduction

Traditionally, cognitive testing is conducted as a single measurement by trained technicians in standardized settings and does not consider within-person variation in cognitive functioning (Sliwinski et al., 2018). This approach is inconsistent with latent-state-trait theory, according to which the measurement of a variable should consider both stable and variable components (Steyer et al., 1999). Furthermore, typical cognitive performance in everyday situations cannot be equated with optimal attentional performance measured under artificial and standardized laboratory conditions. Under these conditions, the influence of social context on cognitive functioning and the interaction of the individual with the environment can never be fully pictured (Moore et al., 2017), which diminishes ecological validity (Allard et al., 2014; Timmers et al., 2014). Repeated ambulatory cognitive assessment, however, may guarantee ecological validity by measuring momentary attention in real-life contexts (Hoc, 2001; Reis, 2012; Timmers et al., 2014; Trull & Ebner-Priemer, 2013). This adds value by providing insights into cognitive trajectories or processes and situational determinants of cognitive performance (Moore et al., 2017). However, ambulatory assessment studies often rely exclusively on self-report measures, which risks overestimating the true association due to common method variance (D. T. Campbell & Fiske, 1959; P. M. Podsakoff et al., 2003), especially when facing abstract constructs, such as cognitive performance (Belenky et al., 2003; Bermudez et al., 2016; Cote & Buckley, 1987; Dorrian et al., 2003).

There has been a repeated call to integrate objective data in occupational research (e.g., Sonnentag et al., 2017). In particular, cognitive performance is crucial to guarantee optimal performance, safety, and well-being at work (Akerstedt & Wright, 2009; Brown, 1994; J. Chung et al., 2015; Harrison & Horne, 2000) and is affected by work characteristics (Qian et al., 2015; Rich et al., 2010). However, the few studies that have applied cognitive tests in real-life occupational settings have either been conducted in a clinical context—for example, linked to alcohol consumption (A. Jones et al., 2018; Tiplady et al., 2009)—or the participants examined (e.g., shift workers, firefighters, pilots) were employed in very specific time-constrained work environments (e.g., Gander et al., 2013; Matsangas & Shattuck, 2020; Patterson et al., 2019; Petrilli et al., 2006; Stout et al., 2021), focusing on performance decline due to shift work and suboptimal sleep behavior without considering fatigue caused by job demands. To date, the use of objective cognitive measures in ambulatory assessment studies with healthy adults is rare (e.g., Daniëls et al., 2020; Verhagen et al., 2019), even though new technologies offer various options to combine subjective measures with objective or physiological measures (Moore et al., 2017) to picture dynamic psychological processes in a person's natural environment (Trull & Ebner-Priemer, 2013).

Measuring cognitive performance using a smartphone-based approach by adapting existing computerized tests successfully applied in traditional cognitive studies is an option for ambulatory cognitive assessment (Calamia, 2019). The challenge for objective ambulatory assessment, however, is to keep the measurements as short as possible while still ensuring measurement quality. As study participants are surveyed repeatedly, the primary goal is to minimize the participant burden, maintain compliance and reduce the risk of external distraction impairing cognitive performance (Sliwinski et al., 2018). However, very little is known about the *shortest* measurement durations of specific cognitive tasks that still provide sufficient measurement quality. The measurement duration of the cognitive tests used in former daily diary studies was either very long (e.g., A. Jones et al., 2018; Tiplady et al., 2009) or chosen based on practical assumptions rather than on empirical evidence (e.g., T. Chung et al., 2020; Lam et al., 2022; Verhagen et al., 2019). There is a need to provide psychometric evidence to encourage researchers to supplement their purely subjective questionnaires with objective performance tests, not only for the validity and reliability of cognitive performance tests in everyday life but also for their sensitivity to systematic within-person changes in cognitive performance, especially over short periods (Sliwinski et al., 2018).

Our major aim is to evaluate whether, how, and when three established cognitive test procedures can be fruitfully applied with smartphones for repeated ambulatory assessments in healthy adult populations to gain insights into cognitive performance patterns. By answering the research question about the *shortest* measurement duration of each test that provides reliable and valid smartphone-based state measures of typical cognitive performance, we pave the way to increase the feasibility of the ambulatory use of three established cognitive test procedures. We further identify associations of their objective outcomes with contextual time-variant variables to give practitioner recommendations for an evidence-based choice among specific tests for different research domains. By providing the digital version of the test procedures used in reliable and valid measurement durations online for free, we help researchers easily implement them in their smartphone-based ambulatory assessment studies.

Theoretical Background

We focus on three tasks that cover different aspects of cognitive performance to answer our research questions: a matching task measuring information processing speed adapted from the Digit Symbol Substitution Task (DSST), a reaction time task measuring alertness adapted from the Psychomotor Vigilance Task (PVT) and a Go–NoGo task measuring cognitive inhibition adapted from the Sustained Attention to Response Task (SART).

Three Established Tests to Measure Objective Cognitive Performance

Digit Symbol Substitution Task. We selected the DSST for our study because DSST performance can be considered a measure of complex attention (Lezak, 1995) and therefore be interpreted as an indicator of general cognitive functioning (Dickinson et al., 2007; Salthouse, 1996) that has low specificity (Amaresha et al., 2014; Sandry et al., 2021) but is highly sensitive to acute and chronic cognitive change (Jaeger, 2018; Sandry et al., 2021).

These characteristics make it a promising test procedure for monitoring momentary cognitive functioning (Jaeger, 2018) in healthy samples working in various occupational domains. In addition, participants in ambulatory assessment studies rated the remote DSST as feasible and acceptable (John et al., 2021; van Oirschot et al., 2020). Participants have reported that the DSST is easy to use and is pleasant and doable (Daniëls et al., 2020; Verhagen et al., 2019). Furthermore, participants were motivated to perform well (Daniëls et al., 2020).

The DSST is a matching task that requires the individual to match random digits to the corresponding symbols based on a provided key (Jaeger, 2018). Originally, the DSST was conducted as a 90–120-second paper and pencil test. The traditional test score is the total number of correctly matched symbols within the predefined measurement time. The outcomes usually used are the number of correct responses (T. Chung et al., 2020; Lam et al., 2022; Suffoletto et al., 2017), the percentage of correct trials, namely, accuracy (Daniëls et al., 2020; Verhagen et al., 2019), and the mean reaction time (T. Chung et al., 2020). When monitoring cognitive change, practice effects within and between days need to be accounted for even if differing versions of the test are presented (Beres & Baron, 1981; van Oirschot et al., 2020; Verhagen et al., 2019).

To date, the DSST and similar tests have mostly been applied to samples of elderly individuals (Brouillette et al., 2013) and clinical patients (Allen et al., 2021; T. Chung et al., 2020; Suffoletto et al., 2017; van Oirschot et al., 2020), in some cases even outside the laboratory in ambulatory assessment designs (e.g., T. Chung et al., 2020; Lam et al., 2022; Suffoletto et al., 2017; van Oirschot et al., 2020). In two studies, healthy adults were included as the control group (Lam et al., 2022; van Oirschot et al., 2020). Only two studies have been conducted that focused mainly on a healthy adult sample: Daniëls et al. (2020) and Verhagen et al. (2019). These studies evaluated the validity of a 30-second smartphone-based DSST by contextualizing cognitive performance with intrapersonal and situational factors in everyday life. Distraction, social context, and location were found to be relevant for cognitive performance (Daniëls et al., 2020; Verhagen et al., 2019).

While the measurement durations of the digital DSST in the studies mentioned ranged from 30 seconds (Daniëls et al., 2020; Verhagen et al., 2019) to 2 minutes (Brouillette et al., 2013), assessment density ranged from an assessment every three days (Lam et al., 2022; van Oirschot et al., 2020) to an hourly assessment (Suffoletto et al., 2017). Overall, there was promising support for both concurrent and construct validity (Allen et al., 2021; Brouillette et al., 2013; T. Chung et al., 2020; Lam et al., 2022; Suffoletto et al., 2017; van Oirschot et al., 2020) and convincing reliability (Brouillette et al., 2013; John et al., 2021; Lam et al., 2022; van Oirschot et al., 2020) among the measurement durations of smartphone-based DSST versions for clinical patient or elderly individual samples, while healthy adult samples remain underrepresented.

In summary, the smartphone-based DSST seems to differ widely in its applied measurement duration, hindering the comparability across studies. Furthermore, the DSST has mostly been applied in the clinical context to date (e.g., T. Chung et al., 2020; Lam et al., 2022), restricting generalization to a healthy occupational population. Information is lacking concerning the minimum measurement duration that provides reliable and valid information about cognitive functioning in a healthy adult sample, as the overarching aim should be to prevent unnecessary burdening of the participants.

Psychomotor Vigilance Task. We further chose the PVT for our study since it depicts real-world risks, especially in the context of tasks that require work-paced or timely responses, such as industrial or transportation tasks (Basner & Dinges, 2011; Dinges, 1995; Philip & Akerstedt, 2006). Sleep deprivation and fatigue are reflected in failures of vigilant attention (Lim & Dinges, 2008); thus, the PVT is commonly used by sleep clinicians. However, fatigue at work can be caused not only by sleep loss but also by work characteristics, such as sustained mental workload or long working hours (Lim et al., 2010;

Peng et al., 2021). Furthermore, fatigue can have serious consequences in several workplaces due to its association with high accident risk and low performance (Basner & Dinges, 2011; Macchi et al., 2002; Peng et al., 2021).

The PVT is a simple visual reaction time task intended to be an indicator of sustained attention, information processing speed, cognitive fatigue, and alertness (Basner & Dinges, 2011; Dinges & Powell, 1985; Doran et al., 2001; Price et al., 2017; van Dongen et al., 2003). A black screen is initially presented. The participant is asked to touch the screen as soon as a checkerboard pattern appears, which is presented at random interstimulus intervals. Among published studies, PVT performance outcomes vary widely, whereas metrics based on response speed and lapses, defined as reaction times that exceed a certain threshold, seem to have the highest sensitivity to sleep loss (Basner & Dinges, 2011).

Since more than a decade, an effort has been made to validate the well-established PVT for ambulatory use with handheld devices and short measurement durations (Lamond et al., 2005; Loh et al., 2004). Most of the validation studies, however, were conducted in the laboratory (Basner & Rubinstein, 2011; Brunet et al., 2017; D. A. Grant et al., 2017; Honn et al., 2015; Lamond et al., 2005; Lamond et al., 2008; Loh et al., 2004; Roach et al., 2006), which prevents generalization due to a lack of ecological validity. Currently, the shortest validated measurement duration for the PVT in these studies—and for technical devices such as tablets, smartphones, or wrist-worn PVT devices—is 3 minutes (Basner et al., 2011; Basner & Rubinstein, 2011; Brunet et al., 2017; D. A. Grant et al., 2017; Matsangas et al., 2017), which still presents a risk in terms of compliance with repeated ambulatory assessments, especially in the occupational context. In regard to validation studies outside the laboratory, M. J. Jones et al. (2018) applied the test in the real-life natural context of female basketball players but unfortunately did not find validity evidence for the 3-minute ambulatory PVT presented on iPads. Price et al. (2017), however, indicated that valid and reliable daily measures of cognitive fatigue can be obtained even with a very short PVT test duration comprising 20 trials in a healthy sample.

While Qian et al. (2015) showed a performance decline in the 20-minute PVT due to heat stress and Peng et al. (2021) showed a mediating effect of fatigue on the association of workplace characteristics and accident risk, little is known about whether and how fatigue caused by work demands manifests in PVT performance. Thus, it remains unclear whether the ambulatory application of the PVT in occupational groups other than those working in time-constrained work environments is fruitful for future research. Furthermore, the common measurement durations remain too time-consuming for ambulatory assessment studies.

Sustained Attention to Response Task. The SART is the third cognitive test applied in our study. We chose this Go–NoGo task because we consider its outcomes relevant in the occupational context, especially for tasks or situations where response inhibition is crucial to avoid errors or accidents (Wilson et al., 2018). The SART requires effortful attention (Grier et al., 2003), and its outcomes are significantly associated with general cognitive failures (Smilek et al., 2010). Furthermore, some work characteristics are associated with attentional degradation measured by the SART (Qian et al., 2015).

The SART was constructed to measure everyday attention failures and provides several indicators of sustained attention (Robertson et al., 1997). During the task, random digits from 1 to 9 appear on the screen. Participants are asked to respond each time any new digit apart from the number 3 appears. The original version has a test duration of 4.3 minutes, which corresponds to 25 passes of digits 1 to 9. The most prominent outcome is the number of commission errors, which represents the number of responses given in a NoGo trial. This outcome can be seen as an indicator of response accuracy, controlled attention (Manly et al., 2003), and response inhibition (Johnson et al., 2007). Additionally, further outcomes can be considered, such as the mean reaction time or the standard deviation of reaction time, which provides information about the stability of the response style. To minimize the influence of the response strategy, Schmidt-Atzert et al. (2004) recommend considering the reaction times of correct trials.

The SART has been applied in some recovery studies. For example, SART performance improvement was observed by Pasanen et al. (2018) following nature walks and restoration-enhancement tasks. To our knowledge, Riedl et al. (2023) is the only study in which the SART was provided ambulatorily on smartphones in the work context and used a measurement duration of under 3 minutes. In this study, it was shown that live-streaming break interventions can have positive effects on SART performance after a work break. One reason for occupational field researchers not using an ambulatory SART in their studies might be the relatively long traditional measurement duration as well as a lack of information concerning the data quality of shortened versions of the task presented on hand-held devices, which highlights the need for empirical evidence concerning the reliability and validity of brief smartphone-based versions of this cognitive test.

Objective Cognitive Performance and Subjective Concentration

One fundamental requirement to perform a cognitive task is concentration, which enables the individual to ignore distractions and focus on the task (Moran, 2012). According to Matlin (2009), attention can also be defined as the concentration of mental activity. Concentration as the conscious decision of an individual to invest mental effort into an aspect of the current situation can be interpreted as one dimension of attention (Moran, 2012). Therefore, concentration can be assumed to be closely related to cognitive performance.

Time-Variant Variables Related to Cognitive Performance

Previous studies devoted to the within-person reliability of various brief cognitive test procedures (e.g., Sliwinski et al., 2018) lack information on whether satisfying reliability coefficients are meaningful for identifying the impact of related time-variant variables, such as mood, fatigue, or stress on cognitive performance. As we focus on healthy adult populations that are largely employed, we further consider the contextual variable of mental demands to be relevant.

Cognitive Performance and Valence. Previous research has shown that emotions and feelings can affect cognitive processes, such as perception and attention, that play a crucial role in the first stages of information processing. Emotions can be characterized dimensionally, for example, by valence-based theories differing between positive and negative emotions (LeBlanc et al., 2015). According to broaden-and-build theory (Fredrickson, 2001), positive emotions broaden individuals’ scope of attention and cognition. Consistent with this theory, Fredrickson and Branigan (2005) demonstrated that positive emotions lead to better scores in a visual processing task. Additionally, medical students in the positive-affect condition were more efficient in an anagram task than participants in the control group, whereas their accuracy did not significantly differ (Isen et al., 1991). Furthermore, positive emotions of athletes were significantly associated with performance-relevant focus and therefore promoted concentration and performance (Vast et al., 2010). When participants reported increased negative affect in the study of Brose et al. (2012), they showed poorer working memory performance. In further studies by Brinker et al. (2013), negative mood significantly predicted correct hits in cognitive tests when the cognitive load was low and errors of inhibition when the cognitive load was low or high. Furthermore, in an ambulatory assessment study by Verhagen et al. (2019), mood correlated with cognitive variation measured eight times per day using a 30-second smartphone-based DSST in a sample of healthy adults. Overall, the broaden-and-build theory and previous empirical findings lead to the assumption that cognitive performance is positively associated with momentary valence.

Cognitive Performance and Arousal. The level of arousal can also impact cognitive performance. Regarding subjective arousal states, two dimensions can be distinguished:

energetic arousal (energy vs. fatigue) and tense arousal (tension vs. calmness; R. E. Thayer, 1990, 1997).

Energetic Arousal. Energetic arousal is typically seen as a performance facilitator (G. Matthews & Westerman, 1994) since the subjective energy level may indicate the extent of available attentional resources (Hirst & Kalmar, 1987; G. Matthews & Davies, 2001). This effect becomes especially evident when task difficulty is high (G. Matthews et al., 1990). Overall, this leads to the assumption that when individuals subjectively feel energetic, more resources are available, and therefore, better cognitive performance is shown.

Tense Arousal. In contrast, according to the attention-depletion hypothesis, tense arousal depletes attentional resources (Sliwinski et al., 2006). It is assumed that more resources are available when the stress level is low than when it is high, predicting a negative within-person correlation between experienced stress and cognitive performance. Resource depletion can impair cognitive processing when it is effortful and therefore depends on available resources (Kahneman, 1973; Oei et al., 2006). Eysenck et al. (2007) state in Attentional Control Theory (ACT) that situational stress is associated with impaired attentional control, especially when the task is highly demanding. According to the ACT, situational stress mainly affects the central executive functions inhibition and shifting of attention and, to a lesser extent, memory updating (Miyake et al., 2000).

In line with the assumptions concerning tense arousal, in a study by Sänger et al. (2014), the error rate of stressed participants was increased in comparison with those in the control group, especially when top-down control was necessary to solve luminance detection tasks. Shields et al. (2016) conducted a meta-analysis and determined that a negative stress effect was evident for working memory tasks, cognitive flexibility tasks, and cognitive inhibition tasks, such as the SART, or simple reaction time tasks. Sliwinski et al. (2006) revealed that situational variability in stress predicted attentional performance in a working memory task within persons, with slower reaction times detected on stressful days. However, stress effects did not become evident when the tasks were performed in simple versions imposing lower working memory demands.

Stress-related performance effects have also been found in occupational samples, where stress was found to be negatively associated with working memory and work performance in health professionals (Allan et al., 2014; Cheung & Au, 2011; A. Harvey et al., 2012; LeBlanc, 2009; Pottier et al., 2013) and special operations soldiers (Morgan et al., 2006). Furthermore, stress is a very relevant outcome in the occupational research context, as work stress and general stress correlate significantly with occupational cognitive failures (Hussain et al., 2019; Wadsworth et al., 2003), which can in turn translate into workplace accidents or injuries and patient safety incidents (Day et al., 2012; Y.-M. Park & Kim, 2013; Wadsworth et al., 2003). Overall, the theoretical assumptions and previous empirical findings indicate that performance in cognitive tasks is enhanced when tense arousal is lower, meaning that individuals feel calmer (R. E. Thayer, 1990, 1997).

Cognitive Performance and Mental Demands. In the occupational context, it is particularly relevant to consider demands with respect to cognitive performance. Young and Stanton (2002) state in their Malleable Attentional Resources Theory (MART) that cognitive performance decreases as a consequence of cognitive underload. In the frame of their theory, the authors point out that attentional capacity can temporarily change according to the mental demands that an individual is facing. For example, low mental demands can lead to a reduced attentional capacity and a performance deficit in subsidiary cognitive tasks due to decreasing cognitive resources. To conclude, according to the MART, low mental demands can be considered detrimental to cognitive performance. This observation is further supported by the results of Liao and Moray (1993), showing that the information processing time when completing cognitive tests is faster when facing increased time pressure, which might be linked to an increased attentional capacity. Furthermore, de Grip et al. (2008) found a cognitive decline in highly educated employees who worked in unchallenging jobs for which they were overqualified. The theoretical conclusions and previous empirical findings suggest a positive relationship between cognitive performance and cognitive demands.

The Present Study

Although there is a great need to draw solid conclusions about the influence of occupational psychosocial factors on cognitive performance in healthy samples, occupational studies conducting ambulatory cognitive assessment are strongly underrepresented. This lack of research may be because most well-established cognitive test procedures have rarely been validated for efficient ambulatory use in healthy samples. Due to the traditional measurement procedures in the laboratory, the application of cognitive tests might often be assigned to long measurement times, which is particularly problematic in repeated surveys conceived at the workplace. This effect leads to our first two research questions: What is the shortest measurement duration of the smartphone-based DSST, PVT, and SART that provides *reliable* measures of within-person change in cognitive performance? (RQ1) Do the shortened reliable smartphone-based DSST, PVT, and SART produce *valid* measures of cognitive performance? (RQ2)

Furthermore, we aim to determine whether the brief test versions are sensitive to relationships between cognitive performance and related time-variant variables such as valence, energetic arousal, calmness, and preceding mental demands (Sliwinski et al., 2018). Therefore, we aim to answer our third research question: Are the brief smartphone-based DSST, PVT, and SART significantly associated with related time-variant variables? (RQ3) By answering this question, we intend to provide an outlook on potentially fruitful fields of application.

Method

Sample and Procedure

The study was conducted among first-year psychology students at a German university. The study design covered two full weeks, including 14 days from Monday to

Sunday. At the beginning of the study period, the participants answered a short one-time smartphone survey including demographic variables and demos of the three cognitive tests. Each day, at three semirandom time points, the students received a smartphone alert that announced a smartphone questionnaire including a small set of subjective items and, subsequently, one of three short cognitive tests. The cognitive tests were presented one at a time to keep momentary measurement durations short and to avoid the influence of mental fatigue on subsequent test performance (Kato et al., 2009). Each cognitive test was presented once a day. One alert appeared randomly between 9 a.m. and 1 p.m., one between 1 p.m. and 5 p.m. and one between 5 p.m. and 9 p.m. Alarms could be postponed for up to 90 minutes and rejected. There was a minimum break of 2 hours between the alarms.

As our research questions focus on level 1 effects, we aimed for a minimum sample size of $N_2 = 40$ (Arend & Schäfer, 2019). Forty-seven students registered for the study. One was excluded because the criterion of at least one completed measurement per cognitive test was not fulfilled. Five students were male, 40 were female, and one did not provide any demographic information. The participating students were aged between 18 and 42 (M = 20.27; SD = 3.99). The remaining 46 students provided 1,706 valid daily measurements within the foreseen 14-day assessment interval, covering 575 valid data sets for the PVT and 566 and 559 valid data sets for the DSST and SART, respectively, corresponding to a compliance rate of 88.30 percent. Participating students were credited with experimental subject hours depending on their compliance. The ethical aspects of the study were evaluated and approved by the ethics committee of the Catholic University of Eichstätt (approval no. 088–2021). RGPD guidelines were followed, and informed consent was obtained from all participants. The participants were informed that they could withdraw their consent anytime during the assessment period without risking any negative impact on their performance evaluations or relations with their professors.

Measures

Unless otherwise stated, variables were measured on a seven-point Likert scale from *strongly disagree* (1) to *strongly agree* (7). In the interest of parsimony in repeated measures, we used a single-item scale for subjective concentration, which, according to R. A. Matthews et al. (2022), does not raise concerns about unreasonable losses of psychometric goodness criteria. As this study was part of a larger research project, further variables concerning sleep, memory, and preceding concentration difficulties were assessed in the questionnaires. However, these additional variables were not included in our analyses and therefore will not be described in more detail.

Subjective concentration. We measured difficulty in maintaining focused attention performance in the one-time smartphone survey at the beginning of the study period with the German version of the Attention and Performance Self-Assessment by Bankstahl and Görtelmeyer (2013). An exemplary item is “In the last 4 weeks, I was only able to concentrate for a very short period of time”. Momentary subjective concentration was recorded situationally with the item “At the moment I can concentrate very well” (Jacobs, 2014).

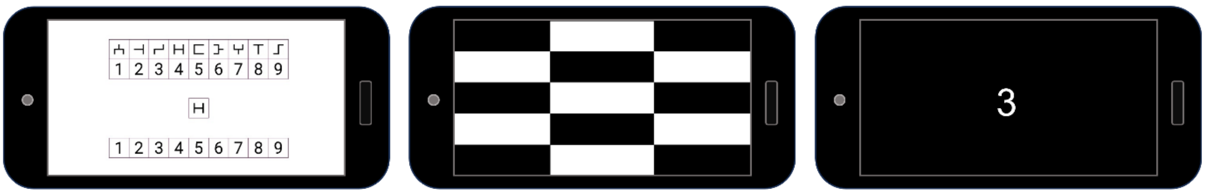
Subjective Valence and Arousal. Momentary mood was assessed with the short scale of Wilhelm and Schoebi (2007) covering the 3 basic mood dimensions with two bipolar items each: Valence (discontent vs. content and unwell vs. well), calmness (agitated vs. calm and tense vs. relaxed), which represents a low level of tense arousal (R. E. Thayer, 1990, 1997), and energetic arousal (tired vs. awake and without energy vs. full of energy).

Subjective Mental Demands. We further included typical situational demands of university students that are similar to the demands of high-knowledge workers. Our goal was to efficiently represent a broad spectrum of mental demands. Therefore, sensory, quantitative, and cognitive demands were included referring to a reference time frame of the preceding two hours. Oriented toward the German version (Nübling et al., 2005) of the Copenhagen Psychosocial Questionnaire (COPSOQ; Kristensen et al., 2002), sensory demands were captured with the item "…my activities required a high degree of concentration", cognitive demands were surveyed with the item "…I had to be attentive to many things at the same time", and quantitative demands were rated by the item "…I was under time pressure". The three items were combined into one scale. The individual-level reliability estimate of these three items is .77 (Bonito et al., 2012), which can be considered respectable (de Vellis, 1991).

Objective Cognitive Performance. Three cognitive tests with a total duration of approximately 3 minutes each were included in the study. The first task was a 180-second matching task adapted from the Digit Symbol Substitution Task (DSST; Boake, 2002; Wechsler, 1939). Throughout the task, random symbols appeared consecutively in the center of the screen (see Figure 2.1). The participant was asked to match these symbols to the correct digit in the bottom response bar with the help of the upper matching bar. The digit-symbol assignment defined in a table on top of the screen varied with each measurement occasion. Response times and the number of errors were recorded.

Figure 2.1

Screen Representations of the Digit Symbol Substitution Task, Psychomotor Vigilance Task, and Sustained Attention to Response Task



Additionally, a simple reaction time task similar to the Psychomotor Vigilance Task (PVT; Dinges & Powell, 1985) was presented in a 48-trial version. A black screen was initially shown, and the participants were asked to touch the screen as soon as a checkerboard pattern appeared (see Figure 2.1). The interstimulus interval varied from 2000 ms to 5000 ms. Reaction times were recorded and considered valid between 100 ms (Basner et al., 2011) and 30000 ms.

Furthermore, a 135-trial Go–NoGo task similar to the Sustained Attention to Response Task (SART; Robertson et al., 1997) was presented. In this task, digits from 1–9 appeared for 250 ms in a random order in the middle of the screen (see Figure 2.1). In between the digits, a black screen was shown for 900 ms. Reaction time and commission errors were recorded.

Software and Hardware

All items were presented in the movisensXS application (movisens GmbH, Karlsruhe, Germany) on an Android 7.0 smartphone with a 5.0" display (1080x1920 pixels). Response times were recorded in milliseconds with one decimal. The cognitive tests were performed within the MovisensXS smartphone application using Presentation® software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA, {HYPERLINK "www.neurobs.com"}). We used code provided by Neurobehavioral Systems and adapted it for smartphone use to program the cognitive tests.

Data Analysis

We focused on six cumulative test segments from a duration of approximately 30 seconds to a duration of approximately 3 minutes for each test to answer the first research question on identifying the shortest measurement duration for each of the three test procedures that provides reliable measures of within-person change in typical cognitive performance. The programming of the DSST was not based on a fixed number of trials but on a fixed measurement duration of 180 seconds. Each test segment was conservatively set to 15 trials to prevent a >5% loss of DSST datasets for the comparative analysis. In the PVT, 8 trials represent one test segment. As the original SART consists of 25 passes of digits 1 to 9 (Robertson et al., 1997), we tried to break down our approximately 3-minute SART—corresponding to 15 passes—into reasonable segments, although commission trials were presented randomly instead of evenly spread. Therefore, we considered test segments of 3, 5, 8, 10, 13, and 15 passes, which corresponded to an average of 3, 5, 8, 10, 13 and 15 NoGo trials, respectively.

As the participants completed the smartphone questionnaires repeatedly over 14 consecutive days, the data show a hierarchical structure with trials nested within days nested within persons. Similar to the procedure of Sliwinski et al. (2018) and Brose et al. (2012), the reliability of change was analyzed by examining systematic within-person variation in the raw outcomes of cognitive performance in accordance with the procedure for diary studies recommended by Cranford et al. (2006) and Shrout and Lane (2012). Regarding the DSST, we focused on the reaction time and the number of errors. For the PVT, reaction time and the number of lapses, defined as reaction times exceeding 355 ms (Basner et al., 2011), were considered to calculate the reliability of day-to-day change. To evaluate the reliability of day-to-day change in the SART, we considered both reaction times in correct trials and commission errors. First, the SPSS (version 29) command VARCOMP was used to decompose the within-person variation into systematic variability (variation across occasions) and error (variation within occasions) for the outcomes considered for the different tests and test segments. For the SART, this was done separately for Go trials and NoGo trials, as these can be seen as indicators for different outcomes—Go trials measure the reaction times of correct trials, and NoGo trials measure commission errors. This led us to the six cumulative test lengths of 24, 40, 64, 80, 104, and 120 Go trials for reaction times and 3, 5, 8, 10, 13, and 15 commission trials. The reliability of day-to-day change was then estimated as recommended in equation (5) of Cranford et al. (2006) and equation (9) of Shrout and Lane (2012). Although according to Nezlek (2017) the standards when interpreting within-person reliability may be less strict than the established standards for between-person reliability, we used the criteria proposed by Shrout (1998) as a conservative reference frame to interpret the reliability coefficients.

For further analyses, the shortest measurement duration that provided at least a fair reliability of change for errors (R_c > 0.40) and at least a moderate reliability of change for reaction time (R_c > 0.60) was selected for each test (Shrout, 1998). Based on the literature (Schmidt-Atzert et al., 2004) and in line with prior studies (e.g., T. Chung et al., 2020; Daniëls et al., 2020; D. A. Grant et al., 2017; Riedl et al., 2023), we focused on the most prominent outcomes for each test. For the DSST, we focused on the number of errors indicating response accuracy and response efficiency was defined as the number of correct trials achieved within a pure reaction time of 1 second. This represents the often-used total number of correct trials within a predefined time span that we could not directly refer to due to the time-based instead of trial-based programming of the test. For the PVT, we considered lapses and mean reaction time. For the SART, we considered commission errors and the mean reaction time of correct trials.

To answer the second research question on the validity of the test versions with the previously defined minimum reliable measurement durations, we calculated within-person and between-person correlations of the person-mean and group-mean centered cognitive outcomes subjective concentration and difficulty in maintaining focused attention performance (Nezlek, 2017).

Multilevel models were built for further analyses to consider the dependency in the nested data set. The statistical analyses were performed with the SPSS command MIXED (version 29). First, null models were built to calculate the variance proportions at level 1 (days) and level 2 (participants) for the 6 different cumulative test segments. We created an increasing count variable separately for each test that we included as a covariate in the multilevel models to test for autocorrelations and linear practice-related trends, gaining information on practice effects due to increasing task experience.

We tested for multicollinearity of the predictor variables by calculating the variance inflation factor for all predictors and centered valence, tense arousal, energetic arousal, and mental demands on the person-mean. We then added the person-centered predictors to the multilevel models (Bryk & Raudenbush, 1992; Nezlek, 2011) to gain insight into the results linked to research question three on the relationship of situational cognitive outcomes with contextual time-variant variables. The linear trend remained in the model to account for practice effects and autocorrelations. Therefore, we specified time series multilevel models, including a fixed effect and a repeated effect for the count variable using restricted maximum likelihood estimation (Hox & McNeish, 2020). Additionally, we specified a random intercept and added random slopes for all within-person variables. As recommended by Nezlek (2011), nonsignificant random slopes (p >.10) were removed stepwise to build parsimonious models (Bates et al., 2015).

Results

Reliability of Day-to-Day Change

All null models showed significant within-subject and between-subject variances, indicating the need for multilevel models. The intraclass correlations of the cognitive outcomes ranged from .16 (mean reaction time, 8-trial PVT) to .60 (mean reaction time of correct trials, 117- and 135-trial SART; see Table 2.1). Furthermore, the subjective variables showed fundamental proportions of within-subject variance (see Table 2.2).

Table 2.1

Intraclass Correlations for Different Objective Outcomes and Increasing Numbers of Cumulative Test Segments

	Number of Cumulative Test Segments					
Objective Outcome	1	2	3	4	5	6
DSST errors	.19	.28	.31	.34	.38	.42
DSST response efficiency	.34	.45	.47	.50	.53	.53
PVT lapses	.37	.44	.46	.49	.50	.53
PVT mean reaction time	.16	.25	.28	.29	.27	.27
SART commission errors	.17	.24	.33	.41	.53	.59
SART mean reaction time of correct trials	.46	.49	.55	.57	.60	.60

Note. $N_2 = 46$, $N_{1\ DSST\ segment\ 1\text{-}3} = 566$, $N_{1\ DSST\ segment\ 4} = 565$, $N_{1\ DSST\ segment\ 5} = 562$, $N_{1\ DSST\ segment\ 6} = 545$, $N_{1\ PVT} = 575$, $N_{1\ SART} = 559$. DSST = Digit Symbol Substitution Task. PVT = Psychomotor Vigilance Task. SART = Sustained Attention to Response Task. One DSST test segment refers to 15 trials. One PVT test segment refers to 8 trials. The cumulative SART test segments refer to 27, 45, 72, 90, 117, and 135 trials, respectively.

Table 2.2

Descriptive Statistics of the Study Variables for the 90-Second DSST, the 30-Second PVT, and the 90-Second SART

Variable	*M*	SD_w	SD_b	*ICC*	1	2	3	4	5	6	7	8	9	10	11
1. DSST errors	1.84	1.80	1.36	.31		-.41**	.00	-.04	.07	-.03	-.06	.00	-.11**	-.12**	-.11*
2. DSST response efficiency	0.64	0.07	0.08	.47	-.33*		-.01	.06	-.01	.02	.10*	.07	.10*	.10*	.10*
3.PVT lapses	1.28	1.33	1.12	.37	.11	-.24		.33**	.03	-.03	.00	.04	-.01	-.08	-.03
4. PVT RT	314.72	190.70	98.76	.16	-.01	-.29	.80**		-.02	-.05	-.04	-.04	-.09*	.00	-.09*
5. SART commission errors	5.13	1.85	1.46	.33	.47**	-.16	.19	.13		-.33**	.05	-.05	.04	.00	-.00
6. SART RTC	285.30	42.79	50.08	.55	-.39**	-.04	.19	.17	-.69**		-.02	.03	-.05	-.10*	.01
7. Energetic arousal	3.97	1.14	0.61	.20	-.42**	.15	-.21	-.15	-.46**	.30*		.13**	.35**	.10**	.46**
8. Calmness	4.42	1.10	0.68	.26	-.35*	.16	-.12	-.07	-.23	.12	.61**		.57**	-.24**	.21**
9. Valence	4.65	1.07	0.67	.27	-.33*	.17	-.23	-.13	-.34*	.14	.65**	.81**		-.05*	.28**
10. Mental demands	2.34	1.42	0.71	.18	.20	-.19	.22	.22	.18	-.14	-.34*	-.40**	-.37*		.05*
11. Subjective concentration	1.28	1.13	0.59	.20	-.28	.05	-.02	.03	-.40**	.28	.71**	.63**	.61**	-.05	
12. Focused attention maintaining difficulty	1.67		0.59		.32*	-.30*	.07	.19	.35*	-.23	-.47**	-.27	-.38**	.20	-.37*

Note. $N_2 = 46$, $N_{1\ DSST} = 566$, $N_{1\ PVT} = 575$, $N_{1\ SART} = 559$, $N_{1\ subjective} = 1706$. Above the diagonal, the within-person correlations are reported, and below the diagonal, between-person correlations based on aggregated data are shown. DSST = Digit Symbol Substitution Task. PVT = Psychomotor Vigilance Task. SART = Sustained Attention to Response Task. SD_w = within-subject standard deviation. SD_b = between-subject standard deviation. *ICC* = intraclass correlation. RT = reaction time. RTC = reaction time of correct trials.

*$p < .05$; **$p < .01$.

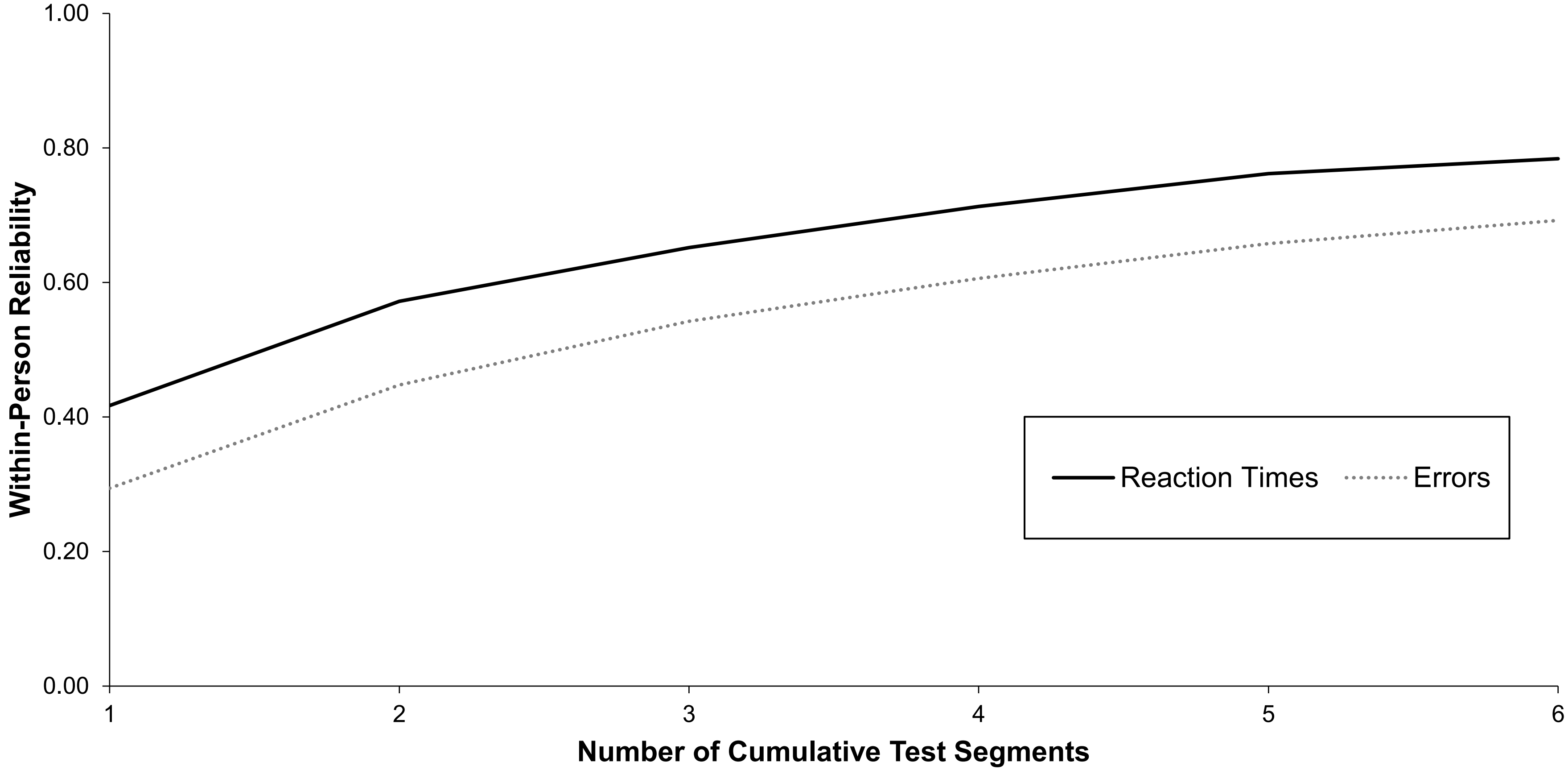
DSST. Based on the criteria of Shrout (1998), errors made in the DSST reached fair reliability from a 60-second measurement duration onward (R_c= 0.45) and moderate reliability from a 120-second measurement duration onward (R_c= 0.61; see Figure 2.2). Reaction times showed a fair reliability from the 30-second measurement duration onward (R_c= 0.42) and reached a moderate level from a 90-second measurement duration onward (R_c= 0.65). Concerning RQ1, these results suggest that a 90-second version of the DSST might be sufficient to provide daily measures of cognitive performance with a fair to moderate reliability of change.

PVT. Reaction times in the PVT showed moderate reliability of change from a 30-second measurement duration onward (R_c = 0.68), reaching a substantial level as of a 2-minute measurement duration (R_c= 0.85; see Figure 2.3). The reliability of day-to-day change in lapses was fair for the 30-second PVT (R_c= 0.59) and reached a moderate level from a 60-second measurement duration onward (R_c= 0.71). Based on these results and referring to our predefined criteria, it can be concluded that a measurement duration of 30 seconds might already assure a sufficient reliability of day-to-day change in reaction time and lapses (RQ1).

SART. Surprisingly, reaction times of correct trials in the SART already showed substantial reliability of change from a 30-second measurement duration onward (R_c = 0.84; see Figure 2.4). Commission errors reached fair reliability of change from 8 NoGo trials onward (R_c = 0.42), corresponding to a 90-second measurement duration. Answering RQ1, these results indicate that the SART with a duration of 90 seconds might provide the optimal compromise of efficient data collection and satisfying reliability of day-to-day change.

Figure 2.2

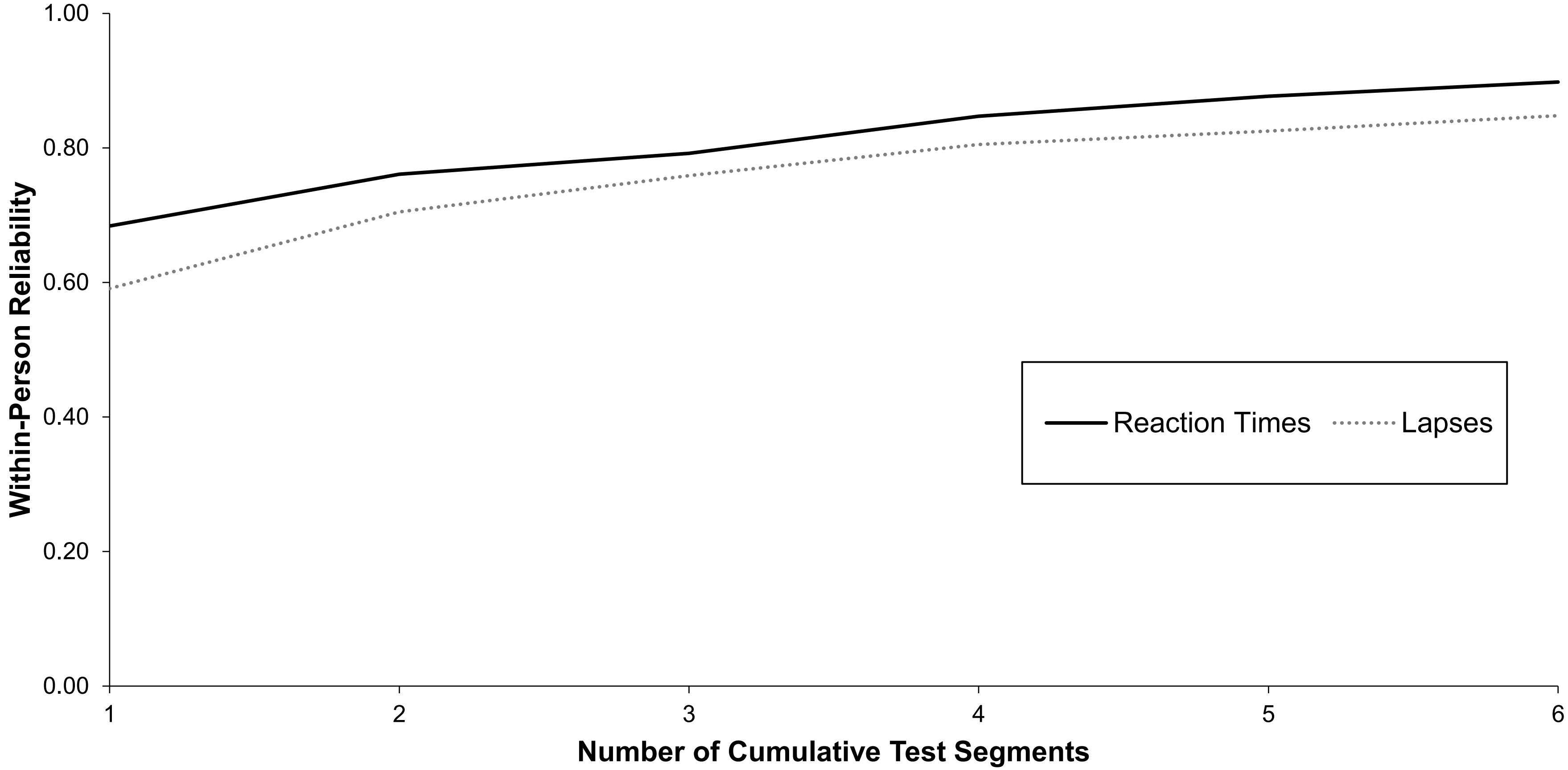
Within-Person Variability of Change for Cumulative Test Segments of the Digit Symbol Substitution Task



Note. One test segment refers to 15 trials.

Figure 2.3

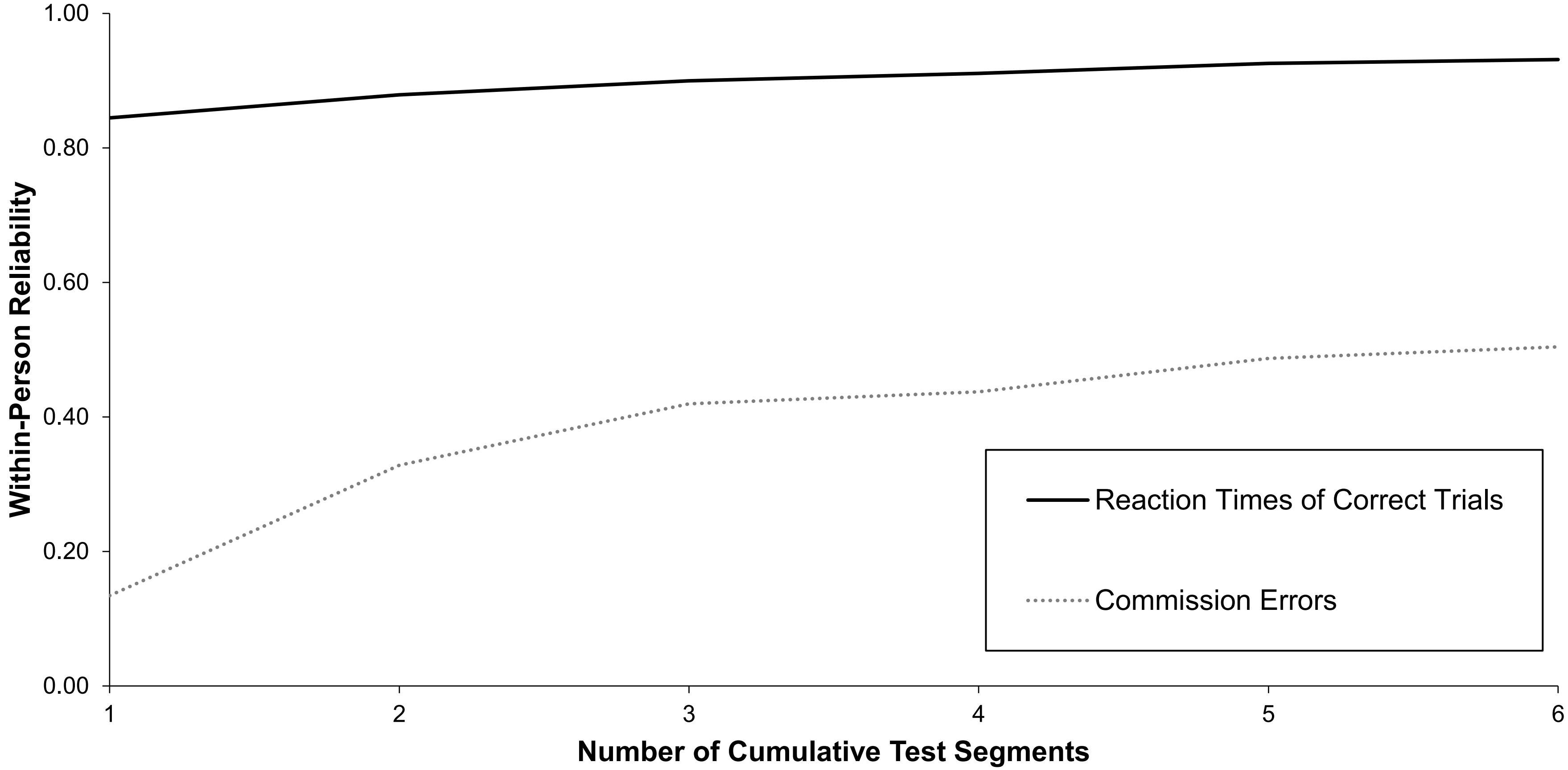
Within-Person Variability of Change for Cumulative Test Segments of the Psychomotor Vigilance Task



Note. One test segment refers to 8 trials. Lapses are defined as trials with reaction times exceeding 355 ms.

Figure 2.4

Within-Person Variability of Change for Cumulative Test Segments of the Sustained Attention to Response Task



Note. The cumulative test segments refer to 24, 40, 64, 80, 104, and 120 Go trials for reaction times of correct trials and 3, 5, 8, 10, 13, and 15 NoGo trials for commission errors.

Validity and Practice-Related Improvement

The variation in test performance across the assessment period is descriptively presented in the supplements (see Table S2.1).

DSST. In the 90-second DSST, which covers 45 trials, participants made on average $M = 1.84$ ($SD = 2.26$) errors, which resulted in a mean response efficiency of $M = 0.64$ ($SD = 0.11$) correct trials achieved within a pure reaction time of 1 second (see Table 2.2). Between-person, participants who reported difficulties in maintaining focused attention made, on average, more errors in the DSST ($r = .32$) and conducted the test less efficiently ($r = -.30$). Furthermore, within-person, DSST performance was significantly correlated with subjective concentration (see Table 2.2), supporting construct validity (RQ2).

While the number of errors in the DSST remained constant ($\gamma = 0.03$, $SE = 0.02$, $p = .21$), an increase in response efficiency ($\gamma = 0.01$, $SE = 0.00$, $p < .01$) was observed with accumulating task experience, indicating a practice-related performance improvement (see Table 2.3). Autocorrelations were not significant for the number of errors ($r = .03$; $p = .60$) or for response efficiency ($r = .04$; $p = .48$).

PVT. In the 30-second PVT, comprising 8 trials, participants reacted on average within $M = 314.76$ ms ($SD = 217.19$) to the stimulus and caused on average $M = 1.28$ ($SD = 1.76$) lapses. Within-person, subjective concentration correlated negatively with the PVT mean reaction time ($r = -.09$), supporting construct validity (RQ2). No significant between-person correlations of PVT performance with subjective concentration or difficulty in maintaining focused attention were found (see Table 2.2).

While the number of lapses increased ($\gamma = 0.07$, $SE = 0.02$, $p < .01$), the mean reaction time remained stable with increasing task experience ($\gamma = 0.66$, $SE = 2.21$, $p = .77$), indicating a performance decrease over time (see Table 2.4). Autocorrelations were significant for the number of lapses ($r = .11$, $p < .05$) but not for mean reaction time ($r = -.01$, $p = .89$).

Table 2.3

Results From Hierarchical Linear Modeling to Predict Digit Symbol Substitution Task (DSST) Performance

	DSST Errors		DSST Response Efficiency	
	Model 1	Model 2	Model 1	Model 2
	Estimate (*SE*)	Estimate (*SE*)	Estimate (*SE*)	Estimate (*SE*)
		Fixed Effects		
Intercept	1.633 (0.251)**	1.579 (0.244)**	0.598 (0.013)**	0.598 (0.013)**
Task experience	0.028 (0.022)	0.034 (0.021)	0.006 (0.001)**	0.006 (0.001)**
Energetic arousal		-0.009 (0.073)		0.004 (0.003)
Calmness		0.084 (0.127)		0.002 (0.004)
Valence		-0.230 (0.115)*		0.004 (0.004)
Mental demands		-0.103 (0.058)		0.006 (0.002)*
		Random Effects		
Energetic arousal				
Calmness		0.330 (0.140)*		
Valence		0.165 (0.092)		
Mental demands				
Level 1 residual variance	3.513 (0.221)**	2.936 (0.201)**	0.006 (0.000)**	0.005 (0.000)**
Autocorrelation parameter	0.028 (0.052)	0.014 (0.054)	0.036 (0.050)	0.041 (0.051)
Level 2 residual variance	1.587 (0.398)**	1.555 (0.383)**	0.005 (0.001)**	0.005 (0.001)**

Note. N_2 = 46 (between person), N_1 = 566 (within person). *SE* = standard error. ***p* < .01, **p* < .05.

Table 2.4

Results From Hierarchical Linear Modeling to Predict Psychomotor Vigilance Task (PVT) Performance

	PVT Lapses		PVT Reaction Time	
	Model 1	Model 2	Model 1	Model 2
	Estimate (*SE*)	Estimate (*SE*)	Estimate (*SE*)	Estimate (*SE*)
	Fixed Effects			
Intercept	0.791 (0.202)**	0.798 (0.202)**	308.639 (21.353)**	307.398 (19.282)**
Task experience	0.069 (0.017)**	0.068 (0.017)**	0.659 (2.210)	0.544 2 (0.121)
Energetic arousal		0.009 (0.054)		-4.663 (7.737)
Calmness		0.021 (0.067)		5.021 (9.572)
Valence		-0.044 (0.069)		-14.380 (13.232)
Mental demands		-0.058 (0.042)		0.125 (5.912)
	Random Effects			
Energetic arousal				
Calmness				
Valence				3188.937 (1028.683)**
Mental demands				
Level 1 residual variance	1.883 (0.121)**	1.883 (0.121)**	39373.542 (2432.695)**	35052.946 (2206.695)**
Autocorrelation parameter	0.108 (0.049)*	0.100 (0.049)*	-0.012 (0.088)	-0.020 (0.073)
Level 2 residual variance	1.097 (0.268)**	1.097 (0.268)**	7430.886 (2167.462)**	4787.433 (1582.640)**

Note. N_2 = 46 (between person), N_1 = 575 (within person). *SE* = standard error. ***p* < .01, **p* < .05.

SART. In the 90-second SART, which includes 72 trials, on average, $M = 7.88$ ($SD = 1.76$) NoGo trials were presented, resulting in $M = 5.13$ ($SD = 2.34$) commission errors on average. The mean reaction time of correct trials was $M = 285.30$ ms ($SD = 66.90$). Between-person, the number of commission errors in the SART correlated significantly with subjective concentration ($r = -.40$) and difficulty in maintaining focused attention ($r = .35$), supporting construct validity (RQ2). No significant within-person correlations were found for SART performance with subjective concentration (see Table 2.2).

The number of commission errors remained stable with increasing task experience ($\gamma = 0.04$, $SE = 0.02$, $p = .08$), while the mean reaction time of correct trials decreased ($\gamma = -1.46$, $SE = 0.65$, $p < .05$), indicating a performance improvement with increasing practice (see Table 2.5). Autocorrelations were significant for the mean reaction time of correct trials ($r = .27$, $p < .01$) but not the number of commission errors ($r = .06$, $p = .25$).

Associations with Contextual Time-Variant Variables

With all variance inflation factors smaller than $VIF = 1.67$, preliminary analyses indicated no risk of multicollinearity for the predictors in the multilevel models (Tabachnick & Fidell, 2013).

DSST. In the 90-second DSST, when controlling for task experience and the influence of the other predictors, fewer errors were made when participants reported a more positively pronounced valence ($\gamma = -0.23$, $SE = 0.11$, $p < .05$; see Table 2.3). Furthermore, participants completed the DSST more efficiently when the preceding mental demands were higher than usual ($\gamma = 0.01$, $SE = 0.00$, $p < .05$). To conclude, valence and prior mental demands were positively related to DSST performance. For energetic arousal and calmness, however, no significant effects were observed (see Table 2.3).

Table 2.5

Results From Hierarchical Linear Modeling to Predict Sustained Attention to Response Task (SART) Performance

	SART Commission Errors		SART Reaction Time of correct Trials	
	Model 1	Model 2	Model 1	Model 2
	Estimate (*SE*)	Estimate (*SE*)	Estimate (*SE*)	Estimate (*SE*)
		Fixed Effects		
Intercept	4.844 (0.264)**	4.821 (0.267)**	296.147 (8.619)**	296.593 (8.627)**
Task experience	0.042 (0.023)	0.046 (0.023)	-1.463 (0.647)*	-1.535 (0.650)*
Energetic arousal		0.092 (0.100)		-0.322 (1.797)
Calmness		-0.214 (0.092)*		2.182 (2.043)
Valence		0.178 (0.100)		-4.667 (2.210)*
Mental demands		-0.040 (0.060)		-2.772 (1.353)*
		Random Effects		
Energetic arousal		0.148 (.081)		
Calmness				
Valence				
Mental demands				
Level 1 residual variance	3.747 (0.240)**	3.524 (0.235)**	2108.380 (157.213)**	2092.363 (157.479)**
Autocorrelation parameter	0.057 (0.049)	0.058 (0.051)	0.270 (0.054)**	0.276 (0.054)**
Level 2 residual variance	1.756 (0.449)**	1.829 (0.462)**	2283.796 (541.043)**	2280.224 (540.919)**

Note. N_2 = 46 (between person), N_1 = 559 (within person). *SE* = standard error. **p < .01, *p < .05.

PVT. Within-person, none of the main effects were significant for the 30-second PVT when controlling for practice effects and the influence of the other predictors (see Table 2.4).

SART. The observed mean reaction times of correct trials in the 90-second SART were faster when the participants reported increased valence (γ = -4.67, *SE* = 2.21, $p < .05$) and when preceding mental demands were higher (γ = -2.77, *SE* = 1.35, $p < .05$; see Table 2.5). Furthermore, calmness is related to a reduced number of commission errors (γ = -0.21, *SE* = 0.09, $p < .05$). Energetic arousal is not significantly related to momentary performance in the 90-second SART (see Table 2.5).

Discussion

The central aim of our study was to provide evidence-based recommendations concerning the ambulatory use of brief smartphone-based versions of established cognitive test procedures in healthy adult populations. The challenge is to keep the measurement duration as short as possible while still assuring data quality. Therefore, we identified the minimum measurement duration of these test procedures that can provide reliable state measures of cognitive performance (RQ1). Subsequently, we evaluated the validity of these brief cognitive measures (RQ2). Furthermore, by identifying significant within-person associations with contextual time-variant variables, namely, valence, energetic arousal, calmness, and mental demands, we aimed to provide an outlook on possible fruitful fields of application for the respective tests (RQ3).

Based on predefined criteria (Shrout, 1998), the 30-second PVT and the 90-second DSST and SART provided the best compromise of brief and reliable measurements. This answers our first research question (RQ1), indicating that the tests in the mentioned measurement durations provide reliable smartphone-based measures of typical performance in field studies with healthy adult populations. Overall, the reliability coefficients of the tests in the chosen lengths are comparable to those of similar tests in former studies (e.g., Sliwinski et al., 2018).

Furthermore, all three cognitive test procedures correlated significantly with subjective cognitive outcomes, supporting the construct validity of the brief test versions (RQ2). While both DSST outcomes and the mean reaction time in the PVT were situationally correlated with subjective concentration, we did not find within-person correlations for the SART outcomes. Nonetheless, commission errors made in the SART were correlated with concentration on a between-person level. Additionally, the between-person correlation of the difficulty in maintaining focused attention with the DSST outcomes further supports construct validity. No significant correlations were found for the number of lapses in the PVT, potentially because 355 ms might not be the threshold that provides optimal sensitivity for the very brief 30-second measurement duration (Basner et al., 2011).

The participants completed the 90-second DSST more efficiently with increasing task experience, indicating a practice-related improvement. This is in line with the results of previous studies (Beres & Baron, 1981; van Oirschot et al., 2020; Verhagen et al., 2019) and therefore further supports construct validity. For the 30-second PVT, we observed a significantly increasing number of lapses over the study period, potentially indicating a lack of motivation, suggesting that this task might be less pleasant than the other tasks, likely resulting from its monotony. With increasing task experience, the 90-second SART was completed faster, whereas the number of commission errors did not significantly increase, overall indicating increasing task proficiency.

Providing evidence for RQ3 concerning mood and in line with the results of Verhagen et al. (2019), momentary valence was significantly associated with an increased performance in the 90-second DSST, as indicated by a reduced number of errors. For the 90-second SART, valence significantly predicted faster mean reaction times of correct trials but not a reduced number of commission errors, which is only partly in line with the results of Brinker et al. (2013), who found that mood significantly correlated with the number of commission errors in Go–NoGo tasks with an interstimulus interval of 1 second. However, the NoGo proportion of the test used in their study was much larger than that used in ours (4 out of 9 vs. 1 out of 9), and the NoGo stimuli varied, while the Go stimulus remained consistent. As the mood effects in this study did not appear for all levels of task difficulty, the different design of our test might explain the absent effect of valence on the number of commission errors in our study. The results for the 90-second smartphone-based DSST and SART reflect that valence plays a crucial role in the first stages of information processing (Fredrickson & Branigan, 2005), supporting the construct validity of these two tasks (RQ2) and indicating that they might be profitable test procedures for application in ambulatory mood research (RQ3).

Concerning momentary levels of energetic arousal, significant within-person correlations were detected for response efficiency in the DSST. However, these correlations did not remain significant when controlling for practice effects and further relevant context variables in the multilevel models. One possible explanation for the absent association of the objective performance indicators with energetic arousal might be that according to G. Matthews et al. (1990), the performance facilitating effect becomes especially evident for tasks with high task difficulty. Our tasks might not be difficult enough to reflect a certain effect, especially due to the reduced measurement duration. Our healthy sample and the measurement period during daytime hours might also play a crucial role, as the variability in energy levels and tiredness might not have been large enough to show a crucial effect on cognitive performance. However, these results are especially surprising for the PVT, which has thus far mainly been applied in the context of sleep deprivation, contradicting the significant correlation of subjective fatigue and reaction time in the PVT in the study of Price et al. (2017). Nevertheless, the crucial difference might be that in their study, the PVT was presented every day at the same time and correlated with subjective fatigue at the day level instead of at the momentary level, as in our study. Furthermore, the construct of fatigue used in their study was of a very broad nature, covering fatigue in general and a lack of initiative or concentration difficulties. Additionally, in other studies, shorter PVT measurement durations were associated with a lower sensitivity to sleepiness (Loh et al., 2004; Roach et al., 2006). Given the limited evidence of sensitivity to changes in energetic arousal, we cannot generally recommend the application of shortened test procedures in studies related to energetic arousal in healthy samples (RQ3). However, the potentially fruitful application of brief tests in the context of time-constrained workplaces that are, for example, linked to shift work causing a larger variability in energetic arousal should be further tested.

In line with the ACT (Eysenck et al., 2007) and former studies that used the SART in recovery research (Pasanen et al., 2018; Riedl et al., 2023), calmness was significantly associated with a reduced number of commission errors in the SART, which indicates enhanced cognitive inhibition. Sliwinski et al. (2006) noted that stress effects do not become evident in simple tasks, such as the PVT. Resource depletion due to stress impairs cognitive processing when it is effortful (Kahneman, 1973; Oei et al., 2006), which might be especially the case for the Go–NoGo SART, which requires top-down control (Sänger et al., 2014; Shields et al., 2016). Additionally, the ACT states that momentary stress especially impedes cognitive control (Eysenck et al., 2007) and central executive functions of inhibition (Miyake et al., 2000). This can explain why no effects of tense arousal were found for the DSST and PVT and further supports the construct validity of the ambulatory SART (RQ2). To conclude, the ambulatory 90-second SART might be a promising test procedure for application in real-life stress and recovery research (RQ3).

In line with the assumptions of the MART and the results of Liao and Moray (1993), preceding mental demands in the 2 hours prior to the objective cognitive assessment were significantly associated with momentary DSST efficiency as well as the mean reaction time of correct trials in the SART. These results support the validity of the 90-second DSST and SART (RQ2) and further indicate that they can be fruitfully applied to learn more about demand-induced effects on mental performance (RQ3). The lack of significant effects of preceding mental demands on PVT performance may be because the PVT is more sensitive to fatigue than to cognitive stimulation. However, our study design did not allow for the detection of distally related strain effects (Meijman & Mulder, 1998), as our reference frame for the mental demands was the preceding two hours, and two-thirds of the measurements took place in the morning or early afternoon.

Practical Recommendations

Overall, due to convincing reliability (RQ1) and validity evidence (RQ2), we recommend the smartphone-based 90-second SART and DSST as well as the 30-second PVT for the repeated assessment of typical cognitive functioning in healthy samples in the real-life context. Furthermore, our results indicate that the brief DSST and SART are meaningful for identifying the relationship between cognitive performance and contextual time-variant variables, such as mood and preceding mental demands, while the 90-second SART appears additionally sensitive to changes in subjectively perceived calmness (RQ3). This leads us to the assumption that both tests may be fruitfully applied in the context of mood research and gainful in clarifying research questions regarding the performance-enhancing effects of mental demands. Additionally, a potential fruitful application of the SART in ambulatory field studies related to stress and recovery can be assumed due to the relationship of the number of commission errors with calmness or tense arousal. We provide the 90-second DSST (http://www.neurobs.com/ex_files/expt_view?id=300) and SART (https://www.neurobs.com/ex_files/expt_view?id=301) for free in the experiment archives of Neurobs Presentation to facilitate its use by other researchers.

Both tests appear appropriate and fruitful to deepen the knowledge on concomitants of mental demands for typical cognitive performance. In particular, the number of errors in the DSST and the mean reaction time of correct trials in the SART appear to be sensitive in this regard. Additionally, the number of correct trials in the DSST and the mean reaction time of correct trials in the SART appear suited to picture the effects of mood on typical cognitive performance. Furthermore, the number of commission errors in the SART appears sensitive to calmness and therefore a promising outcome for ambulatory workplace stress and recovery studies in which objective outcomes are thus far strongly underrepresented (Sonnentag et al., 2017). However, the final choice of the outcome and task should always be guided by the cognitive functions to be investigated. While the DSST can be seen as an indicator of general cognitive functioning (Dickinson et al., 2007; Salthouse, 1996) that has low specificity (Amaresha et al., 2014; Sandry et al., 2021), the SART provides more specific information about controlled attention (Manly et al., 2003), cognitive inhibition (Johnson et al., 2007) and attentional lapses (Manly et al., 2003; Robertson et al., 1997; Smilek et al., 2010).

Limitations and Future Directions

Our aim was to test the reliability and validity of brief smartphone-based ambulatory cognitive tests in a healthy sample and to gain information about which research contexts of related time-variant variables their application might be profitable. Our sample, however, included mainly female psychology students in their early twenties, which reduces the generalizability to other healthy populations. Since access to psychology studies in Germany is strictly regulated by numerus clausus, it can be assumed that the IQ of the sample was above the average IQ of the overall population (Gut et al., 2012). Furthermore, mental demands represent the typical demands of university students or high-knowledge workers. Although we tried to represent a broad spectrum of mental demands by including sensory, quantitative, and cognitive demands, there was a shortcoming of typical demands of other occupational groups, such as emotional demands. Therefore, brief test procedures should be further evaluated in different professional contexts with more heterogeneous samples.

One methodological issue is that splitting the tests into cumulative test segments was quite artificial. For practical reasons, we chose a total measurement duration of approximately 3 minutes. This led to the problem that, for the SART, the six test segments were of unequal length, as the 135 trials could not be reasonably split evenly. Furthermore, the commission trials were randomly spread. Even though the NoGo proportion referred on average to the foreseen proportion for the cumulative test segments, random deviations were possible. Additionally, the programming of the DSST was not based on a fixed number of trials but on the temporal test duration. Due to a lack of temporal information in the output files, we conservatively split the test segments based on practical considerations. Since the participants had performed different numbers of trials in the predefined total measurement interval, the measurement segments defined based on a certain number of trials correspond to individually varying periods. Furthermore, we could not directly evaluate the often-used outcome of total trials achieved within a fixed period (e.g., T. Chung et al., 2020). However, the response efficiency should be a closely related outcome that can be considered equivalent. Further evidence is needed to determine whether the 90-second version of the DSST can replicate our results, especially considering the total number of correct trials.

A potential loss of motivation of the participants to repeatedly perform the 3-minute PVT in our study highlights the need to apply shorter versions of established test procedures in ambulatory assessment studies. Even though the 30-second PVT shows satisfying reliability of change and significant correlations support its validity, we could not identify significant associations with contextual time-variant study variables. Therefore, the shortened version should be further tested in other study designs, for example, after prolonged exposure to demands in time-constrained work environments, to demonstrate its fruitful application in ambulatory assessment studies with healthy adults. Additionally, a potential adjustment of the lapse threshold should be investigated.

As previous studies indicate that cognitive performance differs throughout the day due to circadian variation (e.g., Gaggero & Tommasi, 2023), time-of-day effects on cognitive performance could further support the construct validity of our brief tests. However, as we presented each test only once per day, our study design did not allow us to calculate performance trajectories throughout the day. Future research should take advantage of our shortened smartphone-based test procedures by assessing cognitive performance repeatedly throughout the day, for example, every two hours (Kosenkranius et al., 2023). Such research designs would not only generate more concrete insights about circadian variation in cognitive performance outcomes but also further support the construct validity of the shortened ambulatory cognitive assessments.

In our study, we focused primarily on within-person reliability and momentary associations with time-variant variables, aiming for the use of these brief smartphone-based test procedures in ambulatory assessment research focusing on situational relationships. However, to provide a further outlook, these tests might also be profitable between-person measures. If the aim is to assess typical performance, aggregated repeated within-person measures of cognitive functioning conducted in real-life settings under natural conditions might provide a more accurate estimate than one-time measures in controlled laboratory settings (Moore et al., 2016). This practical use requires further investigation, which in turn can also profoundly supplement the validation of our shortened ambulatory test procedures. Even though concentration is closely related to attention (Matlin, 2009; Moran, 2012), it might be slightly short-sighted to base the construct validity of objective cognitive measures primarily on the correlation with subjective concentration. Individuals do not have a good sense in subjectively judging abstract constructs such as concentration (Bermudez et al., 2016; Cote & Buckley, 1987; Dorrian et al., 2003), which leads to weak correlations with objectively measured cognitive performance (Freund & Kasten, 2012). Thus, demonstrating strong correlations of the mean score of our repeated shortened smartphone-based tests with traditional laboratory test scores might further support the validity of our abbreviated instruments. Generally, even though the assessment of cognitive performance in real-life situations can add valuable insights into typical performance (Allard et al., 2014; Moore et al., 2017; Timmers et al., 2014), great care is needed to avoid assessment biases, for example, by carefully instructing participants to reduce distractions in assessment situations.

Conclusion

Our results indicate that the smartphone-based 90-second DSST and SART as well as the 30-second PVT provide efficient, reliable, and valid state measures of typical cognitive performance in real-life settings. While the DSST and SART appear especially profitable in the context of mood research and for research questions regarding preceding mental demands, the SART appears to additionally provide a fruitful objective indicator for stress and recovery research. We hope our research encourages others to include objective cognitive measures in their ambulatory field studies.

Supplement

Table S2.1

Variation in Test Performance Across the Assessment Period

Variable	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14
1. DSST errors	1.29	2.15	1.64	1.93	1.95	1.90	1.66	1.60	1.88	1.53	1.88	2.19	1.92	2.07
2. DSST response efficiency	0.59	0.61	0.61	0.61	0.64	0.65	0.66	0.65	0.66	0.67	0.67	0.66	0.66	0.67
3.PVT lapses	0.87	0.88	0.76	0.86	1.05	1.39	1.41	1.26	1.50	1.83	1.61	1.44	1.35	1.69
4. PVT RT	396.91	290.42	279.54	282.66	283.28	315.11	306.77	304.47	328.29	325.15	347.89	314.56	313.41	318.43
5. SART commission errors	4.62	4.63	5.03	5.16	5.41	4.62	5.03	5.49	5.05	5.80	5.63	4.76	5.24	5.34
6. SART RTC	312.84	296.47	278.12	279.81	285.91	287.00	283.25	276.16	280.96	274.68	282.26	287.44	266.64	303.81

Note. N = 36-44. DSST = Digit Symbol Substitution Task. PVT = Psychomotor Vigilance Task. SART = Sustained Attention to Response Task. RT = reaction time. RTC = reaction time of correct trials.

CHAPTER III: COGNITIVE PERFORMANCE DURING WORK

Study 2: "Challenge and Hindrance Stressors and Cognitive Functioning Across the Workday: The Moderating Role of Lunch Break Recovery"[2]

Summary

In this daily diary study, we investigated the associations of challenge and hindrance stressors in the morning with objectively measured cognitive functioning at three time points during the workday. We considered lunch break recovery characteristics (break duration, psychological detachment) as moderators of lagged stressor effects. Over two work weeks, 63 knowledge workers answered three questionnaires: before and after the lunch break and at the end of work. The Digit Symbol Substitution Task was used as an objective test of cognitive functioning. Multilevel analyses revealed a positive association of morning challenge stressors with cognitive functioning before the lunch break. Only on days with longer lunch breaks, morning challenge stressors were positively associated with cognitive functioning after the lunch break. Furthermore, only on days with higher lunch break detachment or longer lunch breaks, morning challenge stressors were positively associated with cognitive functioning at the end of work. No significant effects were found for morning hindrance stressors. By objectively assessing cognitive functioning, this study provides a rigorous test of challenge and hindrance stressor effects. Building upon the episodic nature of the Challenge–Hindrance Stressor Framework and assumed underlying resource dynamics, our results highlight lunch break recovery as boundary condition of challenge stressor effects.

[2] Study 2 is an original manuscript by Perzl, Riedl, Thomas, Rigotti, & Haun.
Chapter III is identical to draft version 4.1, 09/11/2025, which has not been peer-reviewed.

Introduction

The Challenge–Hindrance Stressor Framework (CHSF; Cavanaugh et al., 2000) posits that not all stressors are of the same quality. Even though all stressors deplete employees' resources (e.g., energy), hindrance stressors (e.g., hassles, interpersonal conflicts) typically impair performance whereas challenge stressors (e.g., workload, time pressure) can stimulate performance (J. A. LePine et al., 2005; M. A. LePine, 2022).

However, empirical findings on challenge stressor effects are mixed, showing inconsistent effects on self-reported job performance (e.g., Baethge et al., 2016; Xu et al., 2021). Furthermore, although the CHSF (Cavanaugh et al., 2000) highlights the episodic nature of stressor effects (i.e., the exposure to a stressor leading to *subsequent* short-term effects on performance), little is known about the persistence of challenge and hindrance stressor effects across the workday (Pindek et al., 2024). According to the revised CHSF (M. A. LePine, 2022), initial benefits of challenge stressors should fade over time as dealing with job stressors is generally resource-depleting (Meijman & Mulder, 1998). In contrast, depleting effects of hindrance stressors should persist and accumulate over the workday as individuals face further job stressors (Meijman & Mulder, 1998). Contradicting this opposing pattern of lagged challenge and hindrance stressor effects, a recent meta-analysis demonstrated a general pattern of non-significant stressor–performance effects for both challenge and hindrance stressors in within-person studies with lagged designs (Pindek et al., 2024). Thus, it remains unclear *if*, *when,* and *under which conditions* stressors increase or impair performance (M. A. LePine, 2022; Pindek et al., 2024).

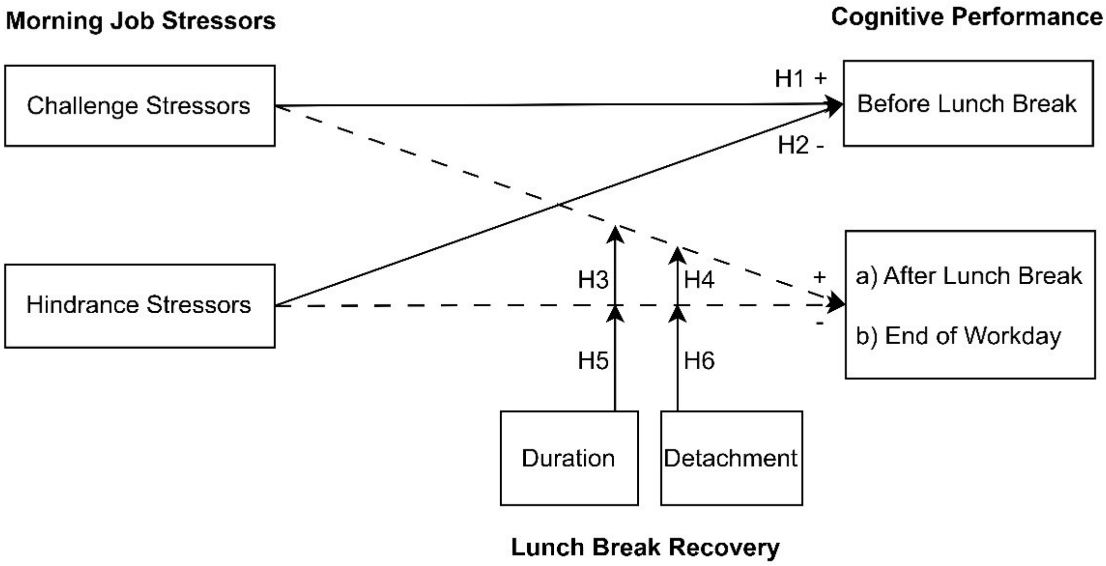
Mixed findings on challenge stressor–performance relationships are not surprising as job performance is a multidimensional construct (J. P. Campbell, 2012). Hence, different performance outcomes (e.g., task performance, organizational citizenship behavior) may potentially generate different results and self-reports may potentially lead to biases (P. M. Podsakoff et al., 2024). To clarify the performance-enhancing potential of challenge stressors independent of specific performance outcomes, we focus on objectively measured cognitive functioning as a general prerequisite of job performance (Lemonaki et al., 2021; Nye et al., 2022).

Non-significant lagged stressor effects could be explained by the moderating role of recovery. According to the revised CHSF, stressor effects vary depending on whether employees "forget to take their foot off of the gas" (M. A. LePine, 2022, p. 239) or take a break to "refuel". As lunch breaks provide the opportunity to restore resources during the workday (Geurts & Sonnentag, 2006), lunch break recovery should be a crucial boundary condition of lagged stressor effects measured after lunch (de Vries-Griever & Meijman, 1987; Sonnentag & Fritz, 2015). Although recovery is an intuitive mechanism for restoring resources (Meijman & Mulder, 1998), it has received little attention in CHSF research (for an exception see Casper & Wehrt, 2022).

With the aim of providing insights on *if*, *when,* and *under which conditions* stressors increase or impair performance, we investigate daily challenge and hindrance stressor effects on cognitive functioning in a sample of knowledge workers. To capture both immediate and delayed effects of morning stressors, we assess employee cognitive functioning at three points during the workday: before lunch, after lunch, and at the end of work. We explore lunch break recovery—specifically, break duration and psychological detachment—as boundary condition of lagged challenge and hindrance stressor effects (see Figure 3.1).

Figure 3.1

Research Model



Note. The dashed lines represent conditional effects that only occur when lunch break recovery is high (challenge stressor effects) or low (hindrance stressor effects).

Our study offers three contributions to the literature: First, we provide insights into the effects of challenge and hindrance stressors on cognitive functioning at work (Hirst & Kalmar, 1987), complementing previous CHSF research on underlying motivational mechanisms of stressor–performance relationships (e.g., Baethge et al., 2018). Following multiple calls (e.g., Chan et al., 2022; Ji et al., 2024; Sonnentag et al., 2017), we employ an objective performance-related measure allowing us to rigorously test the differential stimulating and resource depleting impact of challenge and hindrance stressors. Our objective measurement helps avoid common method bias and reduces confounds from subjective perceptions or social desirability (D. T. Campbell & Fiske, 1959; P. M. Podsakoff et al., 2024).

Second, by examining morning stressors' effects on cognitive functioning at three time points during a workday, we address the episodic nature of the CHSF (Cavanaugh et al., 2000) and expand on the large body of within-person studies using concurrent designs (i.e., measuring stressors and performance simultaneously, typically once per day; Pindek et al., 2024). This allows us to explore both immediate and lagged effects of stressors, providing a deeper understanding of resource mobilizing and depleting stressor effects, ultimately adding a temporal layer to the CHSF's qualitative distinctions.

Third, by integrating recovery research (Meijman & Mulder, 1998; Sonnentag & Fritz, 2015) with the CHSF (Cavanaugh et al., 2000), we address lunch break recovery as potential boundary condition that may explain non-significant findings on lagged stressor–performance relationships. Focusing on within-day recovery, we differentiate between quantitative (break duration) and qualitative (detachment) break characteristics (Chan et al., 2022) to identify which recovery aspects support cognitive functioning under challenging or hindering work conditions. These insights offer actionable guidance for optimizing break strategies to enhance employee functioning at work.

Theoretical Background

The Challenge–Hindrance Stressor Framework

According to the CHSF (Cavanaugh et al., 2000), employees appraise job stressors either as challenge stressors (i.e., opportunities for personal growth and goal achievement) or as hindrance stressors (i.e., tasks that are difficult to control, regardless of coping efforts; Lazarus & Folkman, 1984; J. A. LePine et al., 2005). Workload and time pressure are commonly identified as prototypical challenge stressors (M. A. LePine et al., 2016) known to stimulate performance (J. A. LePine et al., 2005; M. A. LePine, 2022). The performance-stimulating effects can be explained by increased work engagement and resource mobilization (de Vries-Griever & Meijman, 1987; M. A. LePine, 2022). Supporting this, several studies link challenge stressors to higher work engagement (e.g., Tadić et al., 2015) and job performance (e.g., C. Liu et al., 2013; Lu et al., 2016).

In contrast, hindrance stressors—such as interruptions (Baethge et al., 2015), conflicts (M. A. LePine, 2022), and workplace hassles (M. A. LePine et al., 2016)—impede goal progress (Cavanaugh et al., 2000) through disengagement, resource depletion, and emotional strain (M. A. LePine, 2022). Empirical evidence consistently links hindrance stressors to lower work engagement (e.g., Tadić et al., 2015) and poorer job performance (e.g., C. Liu et al., 2013; Lu et al., 2016).

To date, CHSF research has mainly investigated stressor effects on job performance and their underlying motivational mechanisms (e.g., work engagement; Tadić et al., 2015). However, job performance is also determined by cognitive functioning, in particular executive functioning (Lemonaki et al., 2021). In many jobs, employees need to plan their tasks, switch between tasks, or stay focused on their tasks while ignoring distractions to perform at work. Typically, psychometric tests are used to measure executive functioning (Lemonaki et al., 2021). Hence, we chose to measure cognitive functioning with the Digit Symbol Substitution Task (Perzl et al., 2024) as global underlying factor of job performance (Knowles et al., 2015; Lemonaki et al., 2021).

This objective measurement approach contrasts with previous CHSF research using subjective measures. While valuable, subjective assessments risk inflating stressor–performance links due to common method bias (D. T. Campbell & Fiske, 1959; P. M. Podsakoff et al., 2024), particularly in cross-sectional self-report studies (P. M. Podsakoff et al., 2024). Although some studies addressed this issue by using supervisor ratings of performance (e.g., Lu et al., 2016), objective measures provide a stronger alternative as they methodologically separate the assessment of stressors and outcomes and minimize the influence of perceptions and social context (D. T. Campbell & Fiske, 1959; P. M. Podsakoff et al., 2024).

Resource-Mobilizing and Depleting Effects of Challenge and Hindrance Stressors

Resources—defined as limited amount of “fuel” available for information processing (Hirst & Kalmar, 1987) —are crucial for cognitive functioning (Sliwinski et al., 2006; Young & Stanton, 2002) and job performance (Lemonaki et al., 2021). Resources also play a key role in the revised CHSF (M. A. LePine, 2022), explaining the effects of challenge and hindrance stressors on job performance. According to the revised CHSF (M. A. LePine, 2022), challenge stressors motivate employees to mobilize additional resources to work longer or expend more energy (Baethge et al., 2018). The Malleable Attentional Resources Theory (Young & Stanton, 2002) allows us to refine these assumptions for cognitive functioning. According to Young and Stanton (2002), resource pools vary with mental load such that resource pools increase when employees deal with high mental load (Young & Stanton, 2002). For example, when employees face complex, challenging, but doable tasks (i.e., challenge stressors) that require them to deal with a lot of information or focus on multiple things at the same time, they should mobilize attentional resources to accomplish these tasks that can afterwards be directed to the next work task. As challenge stressors pose high mental load on employees, they should prepare them to flexibly react to upcoming stressors (Young & Stanton, 2002). In line with these assumptions, experimental research has shown that when facing higher time pressure, participants invested more effort in their tasks which consequently increased their resource pools (Liao & Moray, 1993). Furthermore, in a diary study with university students, challenge stressors in the previous two hours were positively associated with momentary cognitive functioning (Perzl et al., 2024). Therefore, we propose:

H1: Morning challenge stressors are positively related to cognitive functioning before the lunch break.

In contrast, according to the revised CHSF (M. A. LePine, 2022), hindrance stressors are linked to negative affective experiences such as anxiety, anger, or frustration. Negative affective states deplete resources needed to perform at work (e.g., attention) and are linked to a loss of energy and focus, hence, immediate and delayed performance decrements (Beal et al., 2005; M. A. LePine, 2022). For example, negative valence was associated with reduced cognitive functioning in an experience sampling study with university students (Perzl et al., 2024). Hence, we propose:

H2: Morning hindrance stressors are negatively related to cognitive functioning before the lunch break.

Resource pools are finite (de Vries-Griever & Meijman, 1987) and, according to the CHSF (Cavanaugh et al., 2000), dealing with job stressors generally depletes resources (J. A. LePine et al., 2005; Meijman & Mulder, 1998). Performance impairments become evident when stressors exceed employees' accessible resource pools (Young & Stanton, 2002). Hence, resource availability should affect lagged stressor–performance relationships. Initial performance-stimulating effects of challenge stressors should weaken over time as mobilized resources are depleted (M. A. LePine, 2022). In contrast, the negative impact of hindrance stressors on performance should persist or worsen due to ongoing and accumulating resource loss at work (Beal et al., 2005; M. A. LePine, 2022; Meijman & Mulder, 1998). In line with these assumptions, a meta-analysis of within-person studies (Pindek et al., 2024) found that challenge stressors were directly linked to improved performance but also indirectly to performance declines via increased strain, hence resource loss. In contrast, hindrance stressors were consistently associated with both direct and indirect performance declines.

The Moderating Role of Lunch Break Recovery

The revised CHSF (M. A. LePine, 2022) posits that depleting effects of challenge stressors dominate *if* employees lack recovery. Recovery is defined as "the process of replenishing depleted resources" (Sonnentag & Zijlstra, 2006, p. 331). According to the effort–recovery model (ERM; Meijman & Mulder, 1998), work breaks, such as the lunch break, are critical recovery periods that help replenish depleted resources needed to handle job stressors later in the day.

After several hours of exposure to job stressors, resource pools should be increasingly depleted (Meijman & Mulder, 1998). Lunch breaks interrupt stressor exposure and help replenish resources needed to meet upcoming work demands (de Vries-Griever & Meijman, 1987; Meijman & Mulder, 1998). Hence, lunch breaks should moderate the effects of morning stressors on cognitive functioning in the afternoon (i.e., after the lunch break and at the end of work).

For challenge stressors this means that if resources are replenished during an effective lunch break, stimulating challenge stressor effects should persist throughout the workday (Lemonaki et al., 2021; M. A. LePine, 2022). In contrast, if employees facing high challenge stressors in the morning "forget to take their foot off of the gas" (M. A. LePine, 2022, p. 239), performance-stimulating effects of challenge stressors should fade out (Lemonaki et al., 2021; Young & Stanton, 2002) due to ongoing resource loss (Meijman & Mulder, 1998). In line with these assumptions, previous research identified resource availability (working longer vs. taking time to recover) as boundary condition for the stimulating effects of time pressure on work engagement (Baethge et al., 2019).

The effectiveness of recovery within work depends on several factors (Chan et al., 2022). Building on the ERM (Meijman & Mulder, 1998), we focus on lunch break duration and psychological detachment during the lunch breaks as most essential break characteristics.

Longer breaks support effective recovery by offering more time to interrupt stressor exposure and restore resources (Meijman & Mulder, 1998). For example, in a two-day laboratory study simulating an office environment with a highly repetitive task, longer micro breaks improved recovery (Henning et al., 1989). Daily diary studies also show that longer and more frequent breaks are more effective than shorter, infrequent ones (E. M. Hunter & Wu, 2016), and that lunch break duration is linked to better recovery outcomes (Sianoja et al., 2016). Especially on demanding days, extended breaks are crucial for replenishing resources to sustain cognitive functioning into the afternoon (Geurts & Sonnentag, 2006; Sonnentag & Zijlstra, 2006). Thus, we hypothesize:

H3: On days with longer lunch breaks, there is a significant positive relationship between challenge stressors in the morning and cognitive functioning a) after the lunch break and b) at the end of the workday.

Effective recovery requires a break from stressor exposure, not only physically but also mentally (Meijman & Mulder, 1998). Hence, psychological detachment—mentally distancing oneself from work tasks (Sonnentag & Fritz, 2007)—is a crucial prerequisite of recovery (Etzion et al., 1998; von Dreden & Binnewies, 2017). Research shows that detachment during breaks is linked to better recovery outcomes, such as greater subjective recovery (Sianoja et al., 2016) or restored energy (von Dreden & Binnewies, 2017). Furthermore, psychological detachment is known to buffer resource loss linked to job stressors (Sonnentag & Fritz, 2015) underscoring the role of psychological detachment in helping employees sustain cognitive functioning throughout the afternoon (M. A. LePine, 2022). We therefore hypothesize:

H4: On days with higher lunch break detachment, there is a significant positive relationship between challenge stressors in the morning and cognitive functioning a) after the lunch break and b) at the end of the workday.

For hindrance stressors, ongoing resource loss should cause a decrease in cognitive functioning throughout the whole workday (de Vries-Griever & Meijman, 1987; M. A. LePine, 2022). However, effective lunch break recovery should interrupt the cycle of resource loss by allowing employees to return to work with replenished resources (Meijman & Mulder, 1998). Therefore, effective lunch break recovery should buffer the negative association of morning hindrance stressors with cognitive functioning in the afternoon (Sonnentag & Fritz, 2015). For example, psychological detachment during micro-breaks buffered negative associations between job strain and work engagement in nurses (H. Wang et al., 2022). Based on this reasoning, we hypothesize:

H5: On days with shorter lunch breaks, there is a significant negative relationship between hindrance stressors in the morning and cognitive functioning a) after the lunch break and b) at the end of the workday.

H6: On days with lower lunch break detachment, there is a significant negative relationship between hindrance stressors in the morning and cognitive functioning a) after the lunch break and b) at the end of the workday.

Method

Sample and Procedure

We conducted an experience sampling study with knowledge workers from two German marketing and digital agencies. In one agency, the study was introduced during a staff meeting followed by an email providing study information; in the other, employees were informed via two e-mails. Seventy participants registered using a self-chosen pseudonym on an online platform and received study smartphones containing questionnaires and cognitive tests. To ensure anonymity, study smartphones were distributed in sealed envelopes, either in person or by mail. The study spanned two work weeks (Monday to Friday), beginning with a short demographic survey and a demo of the task measuring cognitive functioning. Each workday, participants completed short smartphone surveys in German at three time points: before and after the lunch break, and at the end of the workday. Each survey concluded with a cognitive functioning test. Six participants who provided no situational data and one who submitted no valid cognitive data were excluded from the analyses.

Of the remaining 63 participants, 27 were male and 36 female. On average, they worked 36.95 hours per week (*SD* = 5.90) and primarily supported clients in strategic HR planning, business development, and marketing. Participants had high autonomy over the timing and use of their breaks[3]. At the agencies' request, no additional demographic data (e.g., age, tenure, role) were collected to ensure anonymity.

Morning job stressors were assessed before lunch; lunch break duration and lunch break detachment were measured after the lunch break. Cognitive functioning was measured

[3] On a five-point scale, participants reported high autonomy when to take a break (*M* = 4.37; *SD* = 0.86) and high autonomy how to spend their breaks (*M* = 4.62; *SD* = 0.79).

before and after the lunch break, and at the end of the workday at the end of each questionnaire. In total, 1,216 situational data points were collected, 437 before lunch, 408 after lunch and 416 at the end of the workday, reflecting an overall compliance of 64.33%[4].

Ethical aspects of the study were evaluated and approved by the ethics committee of the Catholic University of Eichstätt (approval no. 108–2022). Informed consent was obtained from all participants by signed written documents.

Measures

All items were administered via the movisensXS application (movisens GmbH, Karlsruhe, Germany) on Android 7.0 Smartphones with 5.0" displays (1080x1920 pixels). Cognitive tasks were implemented via Presentation® software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA, "www.neurobs.com"). Response times were recorded in milliseconds with one decimal.

Challenge and Hindrance Stressors. To align our study with a recent meta-analysis on within-person concurrent and lagged effects of challenge and hindrance stressors on performance (Pindek et al., 2024), we categorized prototypical challenge and hindrance stressors relevant to the professional context accordingly. We developed two brief measures based on validated instruments (Prümper et al., 1995; Stegmann et al., 2010; Unfallversicherung Bund und Bahn, 2021) using a seven-point Likert scale from *strongly disagree* (1) to *strongly agree* (7). The four-item challenge stressor scale captured time pressure, workload, and cognitive demands such as dealing with a lot of information and focusing on multiple things at the same time. Example items include "This morning, I was under time pressure" and "This morning, I needed to focus on many things at the same time".

[4] True compliance might have been higher as the compliance rate was computed conservatively counting all potential workdays as study days. However, due to data collection taking place during holiday season, some workers might only have been able to participate in a proportion of the study days due to their work schedule. Also, participation was not possible when participants forgot their study smartphone at home.

The three-item hindrance stressors scale assessed perceived hassles, such as missing information, interruptions, and conflict-related stressors, thus, representing relevant obstacles to gain and growth for our sample (M. A. LePine et al., 2016). Sample items include “This morning, I was repeatedly interrupted in my work” and “This morning, I had to deal with negative emotions of other people”. Given the homogeneous sample of knowledge workers, we assumed relatively consistent appraisal of stressors as either challenges or hindrances (Brief & George, 1995; Ji et al., 2024; J. A. LePine et al., 2005).

Both scales were treated as summative measures composed of diverse items with low stressor-consistency. Following prior research (e.g., Schilbach et al., 2023), we do not report Cronbach’s Alpha (Schmitt, 1996; Taber, 2018). To confirm construct validity, we conducted multilevel confirmatory factor analyses using Mplus 8.8 (Muthén & Muthén, 2024), correlating the error terms of two closely related challenge stressor items. The two-factor model ($\chi^2 = 41.66$, $df = 26$, $p < .05$, CFI = 0.98, RMSEA = .04) showed better fit than the one-factor model ($\chi^2 = 56.62$, $df = 27$, $p < .001$, CFI = 0.96, RMSEA = .05; $\Delta\chi^2(1) = 11.72$, $p < .001$), supporting the distinction between challenge and hindrance stressors.

To isolate the lagged effects of morning stressors from the concurrent effects of afternoon stressors on end-of-workday outcomes, we controlled for afternoon challenge and hindrance stressors in our analyses. These were measured at the end of the workday using the same items as the morning stressors but referring specifically to the afternoon period.

Lunch Break Recovery. We measured lunch break duration with an open question: “My lunch break took … minutes today”. To measure lunch break detachment, we adapted the four respective items of the Recovery Experience Questionnaire (Sonnentag & Fritz, 2007) to the break setting by introducing them with “During my lunch break today…”. One sample item is “… I distanced myself from my work” with a five-point Likert scale from *strongly disagree* (1) to *strongly agree* (5). Within-person reliability of lunch break detachment was .93 (Bonito et al., 2012).

Cognitive Functioning. We measured cognitive functioning using a 90-second smartphone-based Digit Symbol Substitution Task (DSST; Wechsler, 1939) validated by Perzl et al. (2024). We chose the DSST for two reasons. First, it captures executive functioning, working memory, and processing speed (Knowles et al., 2015), which correlate not only with various self-reported aspects of job performance, but also with colleague-reported (Lemonaki et al., 2021) and objective performance metrics (Nye et al., 2022). For example, DSST performance correlated significantly with workplace productivity of patients diagnosed with major depressive disorder (Chokka et al., 2019), visual inspection performance in the automotive industry (Murugesan et al., 2025), and driving performance (Seddiq Zai et al., 2022). Second, the DSST is highly sensitive to short-term cognitive change (Daniëls et al., 2020; Jaeger, 2018), reflecting fluctuations in cognitive functioning following stressor exposure (Perzl et al., 2024). This makes it particularly useful for assessing momentary cognitive functioning in settings like knowledge work, where objective job performance indicators are rare (P. M. Podsakoff et al., 2024).

In the DSST, participants match symbols to digits using a reference bar, with digit–symbol pairings randomized across assessments (Jaeger, 2018). Reaction times and errors were recorded. Traditionally, the test score is the total number of correctly matched symbols within the overall assessment time (Jaeger, 2018). To control for smartphone-related timing differences, we calculated information processing efficiency as the number of correct responses within one minute of pure reaction time—capturing both the quality and quantity of performance (Meijman, 1997).

Data Analysis

To ensure that participants had a typical workday with a midday lunch break, we excluded eight workdays with reported work durations of two hours or less and carefully reviewed 39 additional days (4.25–6 hours). Most followed a typical pattern (e.g., 9 a.m. start, lunch at noon, end at 3 p.m.). In three cases, we excluded the after-work questionnaire because work ended immediately after lunch.

We checked the timing between questionnaires to ensure plausibility. One pre-lunch questionnaire was excluded for being completed after the post-lunch survey. In 12 cases, pre-break cognitive data were excluded, and in two cases, post-break cognitive data were excluded, as both were completed within 2 minutes of the next scheduled questionnaire — suggesting late entries. Additionally, we excluded seven detachment reports because lunch break duration was zero.

Given the nested data (days within persons within organizations), we conducted multilevel analyses in Mplus 8.8 (Muthén & Muthén, 2024). Organizational-level variance was negligible (<1% for cognitive functioning; <4% for all study variables), so it was not modeled (James, 1982). Following McNeish (2017), we estimated separate models for each time point (before the lunch break, after the lunch break, at the end of the workday). To control for autoregressive effects, we included the person-mean centered previous cognitive functioning measure of the day as a predictor for cognitive functioning later that day (e.g., pre-lunch functioning predicting post-lunch functioning). To account for linear practice-related trends in the objective outcome (Beres & Baron, 1981; Perzl et al., 2024), we included an increasing count variable for every task completion as covariate. In the next step, morning challenge and hindrance stressors were added as predictors to all models. For post-lunch and end-of-workday cognitive functioning, lunch break duration and lunch break detachment were added as covariates. Including these break characteristics did not change result patterns. In end-of-workday models, we also controlled for afternoon stressors. All predictors and moderators were person-mean centered (Nezlek, 2011), and models included random intercepts and slopes. Nonsignificant random slopes ($p > .10$) were removed for model parsimony (Bates et al., 2015). Finally, lunch break duration and detachment were tested as interaction terms in post-lunch and end-of-day models.

We used the Johnson–Neyman technique to identify regions of significance for the effects of morning challenge and hindrance stressors, depending on lunch break recovery (Lin, 2020). These regions indicate the minimum change in lunch break recovery characteristics at which stressor effects become significant. For practical interpretation, cut-off values for lunch break duration are reported in whole minutes, while those for detachment, due to smaller variance, are presented with one decimal.

Results

Preliminary Analyses

All null models showed significant within- and between-person variance, supporting the use of multilevel modeling. Within-person variance in cognitive functioning ranged from 24–27% across time points. Table 3.1 presents intraclass correlations, means, standard deviations, and within-/between-person correlations. We found a significant increase in cognitive functioning with accumulating task experience ($\gamma = 0.27$, $SE = 0.03$, $p < .001$), indicating a practice-related improvement over time.

Stimulating and Depleting Effects of Challenge and Hindrance Stressors

Supporting Hypothesis 1, we found a significant positive association between challenge stressors in the morning and cognitive functioning before the lunch break ($\gamma = 0.46$, $SE = 0.21$, $p = .026$). Hypothesis 2 was not supported, as morning hindrance stressors were unrelated to cognitive functioning before the lunch break ($\gamma = -0.02$, $SE = 0.24$, $p = .946$). Morning challenges and hindrances were not significantly related to cognitive functioning after the lunch break and at the end of the workday, respectively (see Table 3.2).

Moderating Effects of Lunch Break Recovery

We considered lunch break duration ($M = 43.19$; $SD_w = 13.35$; *Range*: 0–120) and lunch break detachment ($M = 2.91$; $SD_w = 0.97$; *Range*: 1–5) as moderators of the association of morning stressors with cognitive functioning in the afternoon.

Table 3.1

Descriptive Statistics of the Study Variables

Variable	*M*	SD_w	SD_b	*ICC*	1	2	3	4	5	6	7	8	9
1. Morning challenge stressors	4.10	0.90	1.27	.60		.53**	-.07	-.14**	.41**	.17**	.12*	.03	.02
2. Morning hindrance stressors	2.54	0.92	0.84	.36	.69**		-.13*	-.23**	.25**	.42**	.08	.08	.05
3. Lunch break duration	43.19	13.35	15.50	. 47	-.14	-.14		.31**	.03	-.04	-.04	-.02	-.03
4. Lunch break detachment	2.91	0.97	0.83	.29	-.33**	-.25	.31*		-.04	-.19**	.08	.05	.00
5. Afternoon challenge stressors	4.19	0.84	1.39	.68	.91**	.63**	-.21	-.30*		.53**	.15**	.04	.11*
6. Afternoon hindrance stressors	2.62	0.82	0.95	.49	.62**	.87**	-.14	-.27*	.70**		.07	.07	.13*
7. Before lunch break cognitive functioning	34.54	3.73	7.50	.76	-.10	-.05	.28*	.17	-.15	-.12		.26**	.23**
8. After lunch break cognitive functioning	34.40	3.91	7.46	.73	-.15	-.07	.29*	.20	-.25	-.19	.92**		.15**
9. End of workday cognitive functioning	35.24	3.94	8.08	.75	-.07	-.10	.31*	.20	-.11	-.17	.93**	.91**	

Note. N_2 = 63 (between persons), $N_{1before\ lunch\ break}$ = 443, $N_{1after\ lunch\ break}$ = 414, $N_{1end\ of\ workday}$ = 426 (within persons). Above the diagonal the within-person correlations are reported, below the diagonal between-person correlations based on aggregated data are shown. SD_w = within-subject standard deviation. $SD_{b\,=}$ between-subject standard deviation. *ICC* = intraclass correlation.

**p* < .05; ***p* < .01.

Table 3.2

Results From Hierarchical Linear Modelling to Predict Cognitive Functioning

	Before lunch break	After lunch break			End of workday		
	Model 1	Model 1	Model 2a	Model 2b	Model 1	Model 2a	Model 2b
	Estimate (*SE*)	Estimate (*SE*)	Estimate (*SE*)	Estimate (*SE*)	Estimate (*SE*)	Estimate (*SE*)	Estimate (*SE*)
				Fixed effects			
Intercept	31.631 (0.953)**	31.594 (0.983)**	31.577 (0.996)**	31.624 (0.987)**	31.492 (0.996)**	31.479 (1.004)**	31.548 (1.004)**
Autocorrelative factor		0.090 (0.053)	0.083 (0.052)	0.091 (0.053)	-0.029 (0.071)	-0.049 (0.071)	-0.035 (0.071)
Task experience	0.265 (0.028)**	0.223 (0.046)**	0.224 (0.047)**	0.221 (0.045)**	0.243 (0.041)**	0.248 (0.040)**	0.239 (0.040)**
Morning challenge stressors	0.461 (0.207)*	-0.029 (0.347)	-0.001 (0.357)	-0.046 (0.361)	0.054 (0.395)	0.109 (0.363)	0.013 (0.394)
Morning hindrance stressors	-0.016 (0.235)	0.290 (0.526)	0.312 (0.515)	0.317 (0.542)	-0.038 (0.367)	-0.001 (0.368)	0.040 (0.375)
Lunch break duration		-0.005 (0.019)	-0.002 (0.020)	-0.006 (0.019)	-0.004 (0.025)	-0.001 (0.023)	-0.006 (0.025)
Lunch break detachment		0.145 (0.196)	0.121 (0.198)	0.157 (0.194)	-0.014 (0.236)	-0.039 (0.232)	0.041 (0.231)
Afternoon challenge stressors					0.038 (0.407)	0.027 (0.403)	0.050 (0.403)
Afternoon hindrance stressors					0.265 (0.478)	0.247 (0.459)	0.242 (0.476)
Morning challenge stressors*break duration			0.079 (0.033)*			0.066 (0.023)**	
Morning hindrance stressors*break duration			-0.047 (0.035)			-0.020 (0.028)	
Morning challenge stressors*break detachment				0.215 (0.351)			0.588 (0.198)**
Morning hindrance stressors*break detachment				-0.041 (0.208)			-0.208 (0.219)
				Random effects			
Level 1 residual variance	12.886 (1.104)**	15.463 (2.590)**	15.134 (2.452)**	15.422 (2.516)**	15.925 (1.351)**	15.601 (1.323)**	15.667 (1.369)**
Level 2 residual variance	48.304 (9.197)**	47.854 (10.636)**	47.209 (10.132)**	48.056 (10.632)**	47.951 (9.248)**	47.570 (9.120)**	48.592 (9.363)**

Note. $N_{2\ before\ lunch\ break} = 63$, $N_{2\ after\ lunch\ break\ and\ end\ of\ workday} = 60$ (between persons), $N_{1 before\ lunch\ break} = 406$, $N_{1 after\ lunch\ break} = 335$, $N_{1 end\ of\ workday} = 309$ (within persons).

All random slopes were nonsignificant ($p < .10$) and removed stepwise to build parsimonious models.

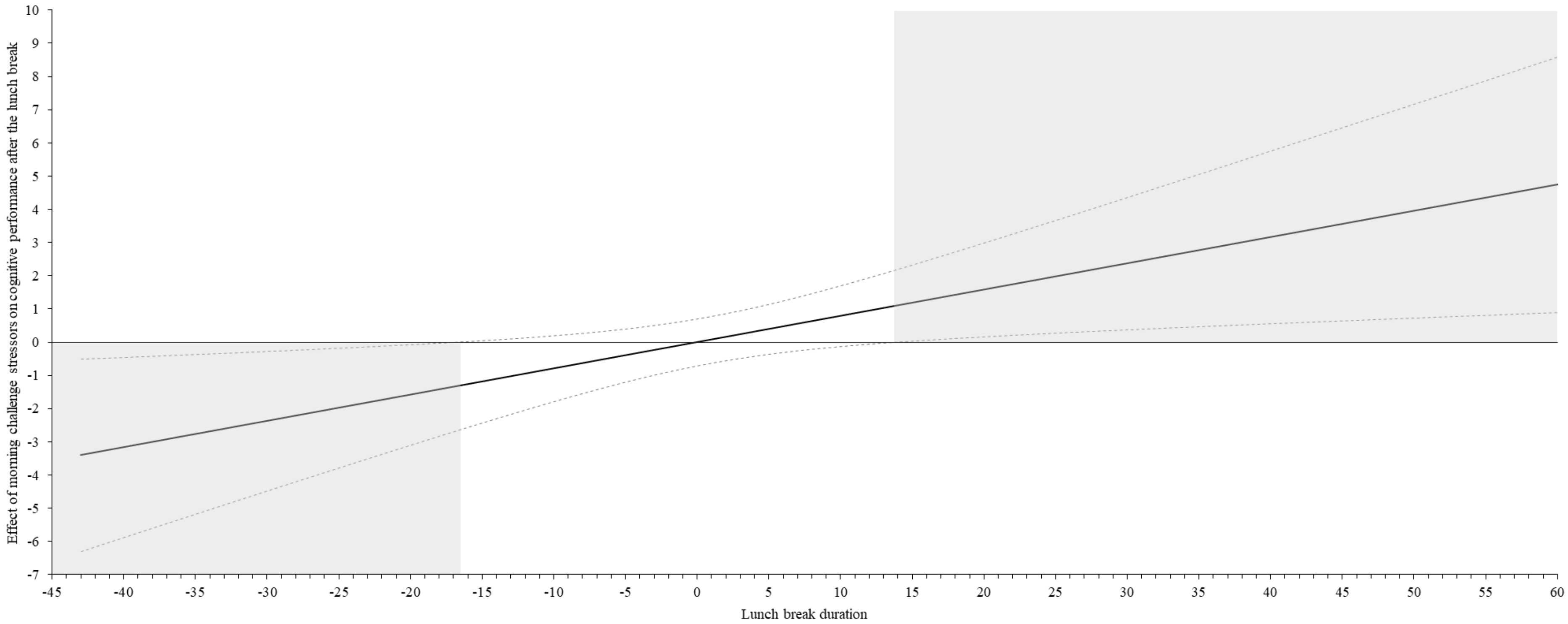
$^{**}p < .01$, $^{*}p < .05$.

Moderated Challenge Stressor Effects on Cognitive Functioning. Lunch break duration significantly moderated the relationship between morning challenge stressors and cognitive functioning both after the lunch break ($\gamma = 0.08$, $SE = 0.03$, $p = .015$) and at the end of the workday ($\gamma = 0.07$, $SE = 0.02$, $p = .003$). Johnson–Neyman plots showed that morning challenge stressors were positively related to post-lunch cognitive functioning when breaks were extended by 14 minutes or more, but negatively related when lunch breaks were shortened by 17 minutes or more (see Figure 3.2). Similarly, at the end of workdays with extended breaks (≥12 minutes than usual) morning challenge stressors were associated with better cognitive functioning, while on days with shortened breaks (≤19 minutes than usual) morning challenge stressors were linked to lower cognitive functioning at the end of the workday (see Figure 3.3). These findings support Hypotheses 3a and 3b, indicating that longer lunch breaks allow for sustained positive associations of morning challenge stressors with afternoon cognitive functioning.

Lunch break detachment significantly moderated the relationship between morning challenge stressors and cognitive functioning at the end of the workday ($\gamma = 0.59$, $SE = 0.20$, $p = .003$), but not immediately after the lunch break ($\gamma = 0.22$, $SE = 0.35$, $p = .540$). Challenge stressors were negatively related to end-of-day cognitive functioning on days with very low detachment (≤1.9 scale points than usual; absolute scale value = 1), and positively related when detachment was minimum 1.7 points above usual (see Figure 3.4). These results support Hypothesis 4b, but not 4a, suggesting that higher detachment facilitates a positive effect of morning challenge stressors on cognitive functioning at the end of the day.

Figure 3.2

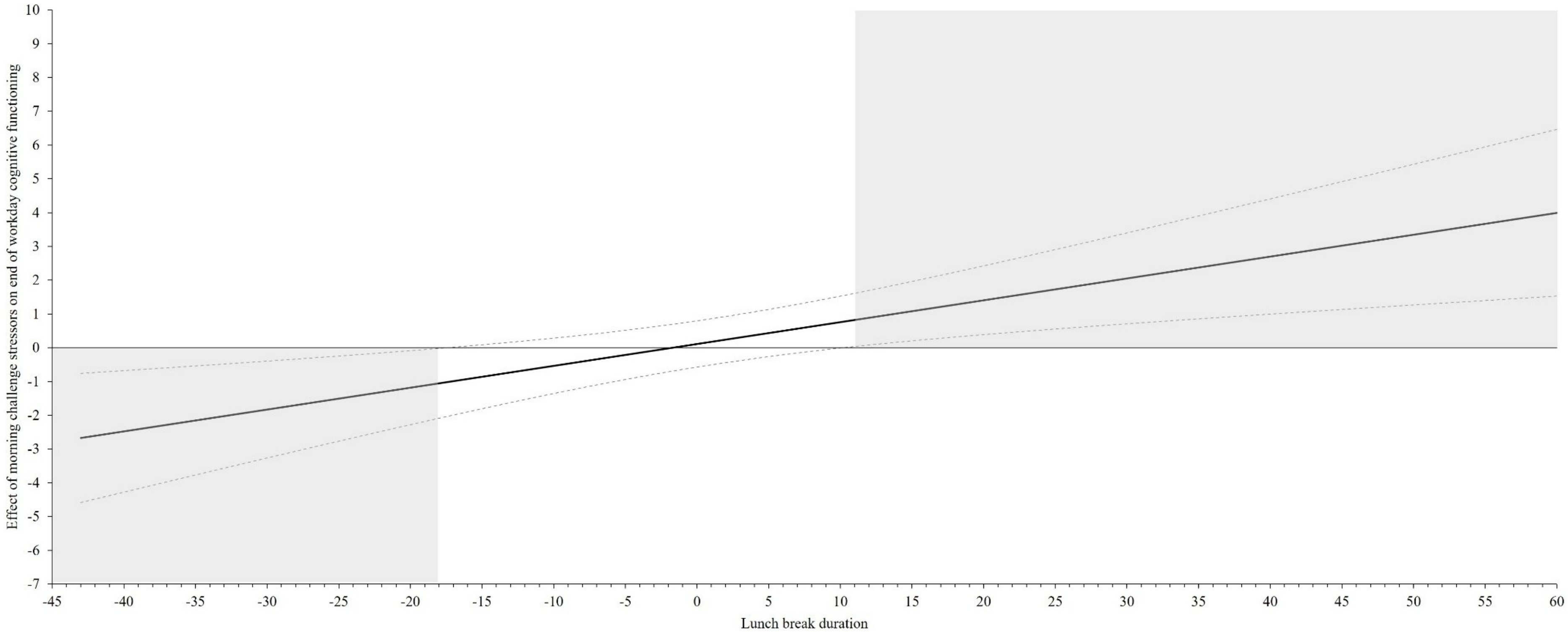
Johnson-Neyman Plot of the Effect of Morning Challenge Stressors on Cognitive Functioning After the Lunch Break as a Function of Deviations From the Average Lunch Break Duration



Note. The black solid line represents the effect of morning challenge stressors on cognitive functioning after the lunch break corresponding to the respective lunch break duration. The gray shaded area indicates the region of significance. Dashed lines show the 95% confidence interval. An x value of 0 corresponds to the average lunch break duration of 43.48 minutes.

Figure 3.3

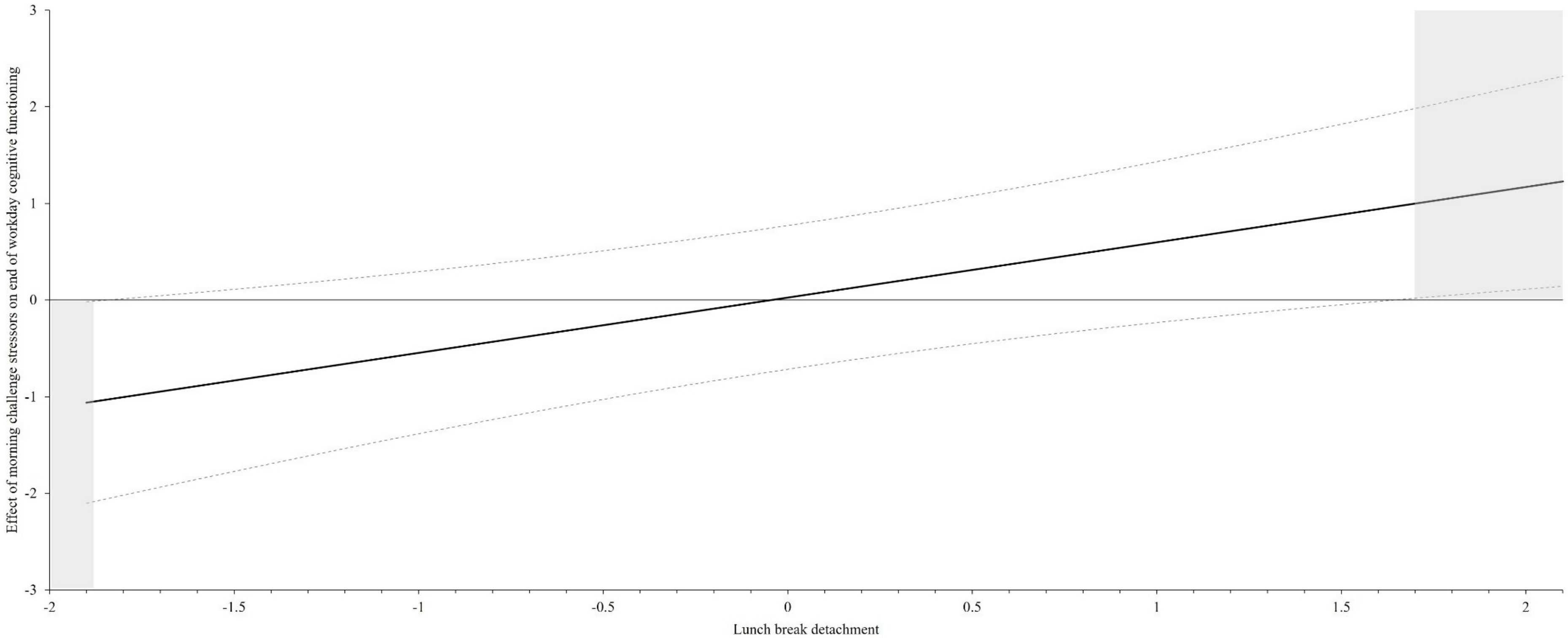
Johnson-Neyman Plot of the Effect of Morning Challenge Stressors on Cognitive Functioning at the End of the Workday as a Function of Deviations From the Average Lunch Break Duration



Note. The black solid line represents the effect of morning challenge stressors on end of workday cognitive functioning corresponding to the respective lunch break duration. The gray shaded area indicates the region of significance. Dashed lines show the 95% confidence interval. An x value of 0 corresponds to the average lunch break duration of 43.48 minutes.

Figure 3.4

Johnson-Neyman Plot of the Effect of Morning Challenge Stressors on Cognitive Functioning at the End of the Workday as a Function of Deviations From the Average Lunch Break Detachment



Note. The black solid line represents the effect of morning challenge stressors on end of workday cognitive functioning corresponding to the respective lunch break detachment. The gray shaded area indicates the region of significance. Dashed lines show the 95% confidence interval. An x value of 0 corresponds to the average lunch break detachment of 2.9 scale points.

Moderated Hindrance Stressor Effects on Cognitive Functioning. Contrary to Hypotheses 5a and 5b, lunch break duration did not significantly moderate the relationship between morning hindrance stressors and cognitive functioning after lunch (γ = -0.05, *SE* = 0.04, *p* = .183) or at the end of the workday (γ = -0.02, *SE* = 0.03, *p* = .476; see Table 3.2). Similarly, no significant moderation effects were found for lunch break detachment, either after lunch (γ = -0.04, *SE* = 0.21, *p* = .884) or at the end of work (γ = -0.21, *SE* = 0.22, *p* = .341; see Table 3.2). Thus, Hypotheses 6a and 6b were not supported.

Discussion

In this daily diary study, we examined *if*, *when*, and *under which conditions* morning challenge and hindrance stressors relate to knowledge workers' cognitive functioning at work using objective assessments. We tested quantitative and qualitative lunch break recovery characteristics (i.e., break duration and break detachment) as moderators of lagged effects. Challenge stressors in the morning were associated with higher cognitive functioning before the lunch break. On workdays with lunch breaks longer than usual, high morning challenges were positively related to cognitive functioning after the lunch break, and on workdays with lunch breaks longer than usual or with higher psychological detachment than usual still at the end of the workday. In contrast, on workdays with lunch breaks shorter than usual or breaks with less psychological detachment than usual, these effects were reversed. Morning hindrance stressors showed no significant associations with cognitive functioning at any time point.

Theoretical Implications

Our study contributes to CHSF research in two ways. First, by using an objective task measuring cognitive functioning, we provide a robust test of the stimulating (i.e., resource-mobilizing) effects of challenge stressors, reducing the risk of bias from common method variance or subjective perceptions. Supporting the theoretical assumptions of the revised CHSF (M. A. LePine, 2022), we found a positive association between morning challenge stressors and cognitive functioning before lunch. This result is in line with previous findings on the relationship of challenge stressors with students' cognitive functioning (Perzl et al., 2024) and employees' subjective job performance (e.g., C. Liu et al., 2013; Lu et al., 2016). Furthermore, this result complements findings on the underlying motivational dynamics of the CHSF (e.g., Baethge et al., 2018) with insights into resources underlying challenge stressor–performance relationships. The finding that hindrance stressors were not significantly associated with a decrease in cognitive functioning may reflect employees' compensatory effort to maintain functioning despite resource loss (de Vries-Griever & Meijman, 1987).

Second, by incorporating the episodic nature of the CHSF (Cavanaugh et al., 2000) and examining the moderating role of recovery for lagged stressor effects, we provide refined insights to the persistence of stressor effects and help explain non-significant findings on lagged stressor–performance relationships (Pindek et al., 2024). Building on recovery literature (Meijman & Mulder, 1998; Sonnentag & Fritz, 2015), our results demonstrate that the lagged association of morning challenge stressors with cognitive functioning in the afternoon depends on recovery conditions, specifically lunch break duration and detachment. These results highlight the crucial role of resources in the revised CHSF (M. A. LePine, 2022) and support prior findings indicating that resource availability is key to stimulating effects of challenge stressors (Baethge et al., 2019). Positive associations on days with effective recovery and negative ones on days with poor recovery illustrate how insufficient recovery can interrupt or reverse gain spirals, leading to performance declines (Baethge et al., 2019; Hockey, 1997).

The finding that lunch break recovery did not moderate hindrance stressor-effects on cognitive functioning may be grounded in the *matching principle* (Ji et al., 2024) stating that the associations between job stressors, job resources, and work outcomes are stronger if they belong to the same domain (emotional, cognitive, physical). While the assessed challenge stressors, psychological detachment, and cognitive functioning all belong to the cognitive domain, the assessed hindrance stressors (e.g., dealing with negative emotions of others) are more emotional in nature and may impact performance primarily through emotional responses such as frustration or rumination (M. A. LePine, 2022; M. Wang et al., 2013) which may be little affected by break recovery.

Third, our study contributes to the recovery literature by deepening the understanding of how workplace stress interacts with lunch break recovery. According to the Stressor Detachment Model (SDM; Sonnentag & Fritz, 2015), psychological detachment can buffer detrimental stressor–strain relationships. By differentiating between challenge and hindrance stressors and demonstrating that detachment during work breaks may help sustain the performance benefits of challenge stressors, we refine the assumptions of the SDM (Sonnentag & Fritz, 2015). Psychological detachment can not only protect against strain when facing job stressors but also boost stimulating challenge stressor effects. Alongside similar effects for break duration, our results highlight the crucial role of effective recovery during work breaks in maintaining and optimizing cognitive functioning at work.

Practical Implications

Our findings highlight the importance of both lunch break duration and detachment for sustaining cognitive functioning at work (Sonnentag et al., 2022). Lunch breaks offer a key opportunity for recovery (Sianoja et al., 2016; von Dreden & Binnewies, 2017), helping employees manage job stressors. Longer breaks can extend the benefits of morning challenge stressors and buffer against declines in cognitive functioning. Since break duration is influenced by both employees and employers (Sianoja et al., 2016), we recommend increasing employee autonomy and encouraging longer breaks, especially after demanding mornings. As employees often shorten breaks on stressful days (Dettmers et al., 2016), recovery education may be a cost-effective way to promote better break use.

Our results also suggest that high levels of lunch break detachment enhance the positive effects of morning challenge stressors later in the workday. Employers can support detachment through activities such as park walks (de Bloom et al., 2017), games (Fourie et al., 2020), relaxation exercises (Sianoja et al., 2018), or by promoting nonwork conversations during shared breaks (von Dreden & Binnewies, 2017).

Although hindrance stressors did not significantly impact cognitive functioning in our study, their negative effects on well-being (J. A. LePine et al., 2005) and work-related performance outcomes (e.g., task performance; Pindek et al., 2024) are well-documented. To reduce these stressors, organizations should ensure access to necessary information and implement structured interaction policies to minimize interruptions.

Limitations and Future Directions

We opted for an a priori categorization of stressors to align with previous research on concurrent and lagged stressor effects (Pindek et al., 2024). To minimize participant burden during three daily assessments including a 90-second cognitive task, we kept questionnaires brief and excluded explicit challenge–hindrance appraisals. Instead, we aimed for consistent appraisals by focusing on knowledge workers in two similar German marketing and digital agencies and selecting prototypical stressors (e.g., workload, interruptions; Brief & George, 1995; Ji et al., 2024). However, while some stressors (e.g., interruptions; Ma et al., 2020) tend to be appraised consistently, others (e.g., time pressure) may vary by situation, contributing to within-person differences in outcomes (Searle & Auton, 2015). The lack of stressor appraisal data may also explain the non-significant effects of hindrance stressors on cognitive functioning (Ma et al., 2021; Pindek & Spector, 2016). Future studies should examine appraisals as potential mediators in CHSF mechanisms (M. A. LePine, 2022).

The homogeneity of our sample and stressors tailored to their professional field limit generalizability. Furthermore, our sample size is rather small compared to typical sample sizes used in daily diary studies (Gabriel et al., 2019). While our selected stressors are common across many jobs, future research should replicate these findings in more diverse settings with larger samples to draw more definite conclusions.

The knowledge workers in our sample reported high autonomy regarding break timing, duration, and activities. As not all jobs offer such autonomy, future research should explore alternative moderators that can prolong the stimulating effects of challenge stressors or buffer detrimental stressor effects. Potential moderators that could help better understand hindrance stressor effects include setting-specific recovery activities (Lyubykh et al., 2022) or social support (Tadić et al., 2015). Furthermore, microbreaks could serve as a compensatory mechanism for insufficient lunch break recovery or enhance resource gain spirals after effective lunch breaks.

Although we used a time-lagged design to study the relationship between morning stressors and subsequent cognitive functioning, causality cannot be definitively determined. Alternative causes, such as common factors, should be addressed in experimental and longitudinal studies. Future research should control for additional covariates (e.g., job resources) to rule out alternative explanations for significant or non-significant stressor effects.

While the use of objectively measured cognitive functioning is a strength of our study, minimizing common method bias (P. M. Podsakoff et al., 2024), in-situ objective assessments may be influenced by uncontrollable factors like distractions (Daniëls et al., 2020). To control for such situational variables, future studies should include relevant covariates (e.g., presence of others). Additionally, while capturing cognitive functioning, we did not assess job performance. However, prior research shows that cognitive functioning is linked to subjective and objective job outcomes (e.g., task performance; Lemonaki et al., 2021; Nye et al., 2022). For a comprehensive empirical test of the revised CHSF (M. A. LePine, 2022), future research should investigate cognitive functioning and work engagement simultaneously as mediators of challenge and hindrance stressor–performance relationships.

Conclusion

Overall, our study emphasizes the crucial role of lunch break recovery in maintaining the stimulating effects of challenge stressors throughout the workday. While morning challenge stressors boosted cognitive functioning before lunch, these effects only persisted into the afternoon when employees took longer breaks or experienced higher psychological detachment during the lunch break than usual. Extending previous research based on self-reported performance and work engagement, our study findings—based on objectively measured cognitive functioning—offer robust evidence regarding *if*, *when*, and *under which conditions* stressor effects occur.

CHAPTER IV: COGNITIVE PERFORMANCE AT THE START OF WORK

Study 3: "The Role of Psychophysiological Evening Recovery Trajectories for Next-Morning Energy and Cognitive Functioning: A Multi-Method Experience Sampling Approach"[5]

Summary

Even though recovery is conceptualized as a process of changing psychophysiological states, the temporal characteristics of recovery have rarely been investigated. To address this gap, we investigate subjective (fatigue) and physiological (heart rate variability; HRV) recovery trajectories in the evening after work. Building upon the effort–recovery model (ERM) and the allostatic load model, we further explore the effects of these evening recovery trajectories on next-morning functioning (energy and cognitive functioning). In an experience sampling study covering 200 evenings after work (65 employees participating), we collected hourly self-report assessments of fatigue and state assessments of HRV extracted from continuously recorded electrocardiograms. At the beginning of the next workday, participants reported their current level of energy and completed the smartphone-based Sustained Attention to Response Task (SART), indexing cognitive functioning (cognitive performance and cognitive effort). Latent growth curve models revealed U-shaped fatigue and HRV trajectories in the evening after work. Highlighting the importance of immediate and complete evening recovery after work, the slopes of the fatigue and HRV trajectories showed significant associations with next-morning cognitive functioning, but not with energy levels. By integrating objective recovery indicators, our findings advance the understanding of psychophysiological after-work recovery dynamics and their effects on next-morning functioning, contribute to theoretically refining the ERM, and offer new targets for occupational health interventions.

[5] Study 3 is an original manuscript by Perzl, Schmid, Rigotti, & Haun.
Chapter III is identical to draft version 3.1, 21/01/2026, which has not been peer-reviewed.

Introduction

Recovery from job stress after work is considered a crucial protective factor sustaining employees' energy and performance after stressor exposure at work (e.g., H. Liu et al., 2021; Parker et al., 2020). While employees may be able to leave work-related stress behind and recover quickly after work on some evenings, their recovery process may be delayed or take more time on other evenings (R. S. Grant et al., 2026). Although recovery from job stress is defined and theorized as a dynamic and adaptive process of changing psychophysiological states (Geurts & Sonnentag, 2006; McEwen, 1998; Meijman & Mulder, 1998; Zijlstra et al., 2014), little is known about the temporal characteristics of recovery, that is, how recovery unfolds after the end of the workday.

Typically, recovery research relies on summary retrospective assessments of recovery during a nonwork period (e.g., evening after work; Sonnentag et al., 2008) or state measurements at the endpoint of the recovery process (e.g., momentary affect at bedtime; Hilbert et al., 2025). However, such summary recovery states may mask differences in temporal characteristics of the recovery process. For example, moderate average evening recovery may result from a constant moderate recovery trajectory, an increasing trajectory with low recovery levels at the end of work and high recovery levels at bedtime, a decreasing trajectory, or a U-shaped trajectory.

Initial process-focused approaches suggest that modeling temporal recovery trajectories can advance our understanding of evening recovery and its consequences. For example, a study by Maike Arnold et al. (2023) demonstrated that recovery experiences follow distinct evening trajectories and linear slopes of psychological detachment predicted next-day mood beyond evening averages and endpoint assessments. Similarly, a study by R. S. Grant et al. (2026) found that early, steady recovery trajectories were more advantageous than delayed recovery trajectories for next-morning energy and fatigue and for afternoon work goal accomplishment.

Even though preliminary findings suggest that recovery trajectories are more complex (Maike Arnold et al., 2023), to date, existing evidence on evening recovery processes remains largely confined to linear trajectories (Maike Arnold et al., 2023; R. S. Grant et al., 2026), which risk masking the interplay of recovery and circadian influences on psychophysiological evening states (Meijman & Mulder, 1998; Zijlstra et al., 2014). In contrast to linear trajectories, quadratic trajectories can capture both recovery and circadian dynamics. Consistent with this notion, Maike Arnold et al. (2023) observed a significant quadratic trajectory for mastery (initial recovery-driven increase followed by a circadian-driven decline), while R. S. Grant et al. (2026) reported constantly low linear mastery trajectories across profiles. Furthermore, the predominance of results based on self-reported recovery experiences (Maike Arnold et al., 2023; R. S. Grant et al., 2026) may not generalize to objectively measured physiological recovery indicators (e.g., heart rate variability; HRV), hence, only providing a one-sided perspective on psychophysiological recovery.

To align with recovery definitions and theories emphasizing dynamic psychophysiological change (e.g., Meijman & Mulder, 1998; Zijlstra et al., 2014), we examine psychological (fatigue) and physiological (HRV) recovery trajectories across the evening after work. By modeling quadratic trajectories, we explicitly consider the interplay of recovery after work and circadian influences (Zijlstra et al., 2014). We further test whether temporal characteristics of these evening recovery trajectories (e.g., early recovery onset, extent of recovery before circadian effects dominate) are associated with next-morning functioning, in particular energy and cognitive functioning, two key prerequisites of daily work potential (Meijman & Mulder, 1998) and job performance (J. F. Thayer et al., 2009; Weigelt et al., 2022). In response to calls for more multi-method designs (Sonnentag et al., 2017) and to reduce alternative explanations (e.g., common method variance; P. M. Podsakoff et al., 2024), we incorporate objective measures of physiological evening recovery and next-morning cognitive functioning.

Our study makes several key contributions to the recovery literature. First, by reconceptualizing evening recovery from job stress as a temporal process of changing psychophysiological states (Zijlstra et al., 2014), we address the question of how recovery unfolds after job stressor exposure ends (Sonnentag et al., 2017). Whereas prior research has primarily examined trajectories of fatigue or HRV across the entire (work)day (Baethge et al., 2020; Hülsheger, 2016), our focused examination of the evening period enables a more fine-grained analysis of recovery dynamics. By examining quadratic fatigue and HRV trajectories, we extend prior work on linear evening trajectories of recovery experiences (e.g., R. S. Grant et al., 2026) and more fully capture the interplay of recovery and circadian influences in psychophysiological regulation after work (Zijlstra et al., 2014).

Second, building upon the allostatic load model (ALM; McEwen, 1998), the recovery literature (Geurts & Sonnentag, 2006), and initial trajectory research (Maike Arnold et al., 2023; R. S. Grant et al., 2026), we refine and test theoretical assumptions of the effort–recovery model (ERM; Meijman & Mulder, 1998) by specifying temporal characteristics of 'sufficient' psychological and physiological evening recovery. Linking these temporal characteristics to next-morning energy and cognitive functioning highlights timing, speed, and extent of recovery as potential drivers of next-day functioning at work.

Third, our multi-modal approach to psychological and physiological recovery (Ganster & Rosen, 2013) offers a comprehensive understanding of evening recovery from job stress (Simon et al., 2022). Because psychological and physiological recovery indicators may be differentially shaped by circadian influences in the evening (e.g., Coumel et al., 1994; Hülsheger, 2016), unidimensional assessments risk overgeneralizing and missing meaningful recovery patterns. Including physiological indicators aligns with the psychophysiological recovery frameworks (e.g., McEwen, 1998; Meijman & Mulder, 1998; Zijlstra et al., 2014) and can inform mechanisms underlying perceived recovery (Sonnentag et al., 2017; Steed et al., 2021). Combining energy self-reports with objective cognitive functioning assessments further captures both willingness and capacity to perform (Meijman & Mulder, 1998).

From a practical perspective, by identifying whether specific temporal trajectory features (e.g., earlier recovery onset) relate to next-morning functioning, our findings inform the design and timing of recovery interventions beyond traditional activity-based recommendations (Sonnentag et al., 2017).

Theoretical Background

Job Stress and Recovery

The ERM (Meijman & Mulder, 1998) posits that work taxes employees' resources and destabilizes psychobiological systems as effort is expended to meet job demands. Hence, the ERM (Meijman & Mulder, 1998) suggests that, at the end of work, employees experience psychological (e.g., fatigue) and physiological (e.g., high heart rate) strain (Meijman & Mulder, 1998). In most cases, these short-term strain reactions are adaptive and reversible and do not exceed a certain threshold of harmfulness (Meijman & Mulder, 1998). However, persistent and irreversible negative effects are possible in case of sustained stressor confrontation and insufficient recovery (Meijman & Mulder, 1998).

Recovery is considered the antagonist of job stressor effects, representing "a process of psychophysiological unwinding that is the opposite of the activation of psychophysiological systems during effort expenditure" (Geurts & Sonnentag, 2006, p. 483). Hence, the recovery process after work allows psychobiological systems to stabilize at a baseline level within a certain time after the end of stressor exposure (Meijman & Mulder, 1998). If recovery is quantitatively and qualitatively 'sufficient', work-related strain should diminish shortly after the end of work (i.e., the end of job stressor confrontation; Meijman & Mulder, 1998). Inversely, 'insufficient' recovery during nonwork time (e.g., in the evening after work) can eventually impede employee functioning the next day at work (Meijman & Mulder, 1998).

The ALM (McEwen, 1998) specifies these assumptions for physiological reactions to stressful experiences and can also be applied to physiological reactions to job stressors (Ganster & Rosen, 2013). According to the ALM (McEwen, 1998), and consistent with the propositions of the ERM, physiological stress responses are considered adaptive if they are initiated at stressor onset, sustained until stressor offset, and immediately followed by recovery. For example, when employees face a difficult task at work, their blood pressure increases and stays at an elevated level until the end of the task when the blood pressure should normalize immediately. Based on the ALM (McEwen, 1998), negative long-term consequences (e.g., hypertension) are to be expected in case of delayed recovery, that is, if the physiological stressor response does not cease timely after the end of stressor confrontation (e.g., the end of work).

Evening Recovery Processes

The evening after work is the nonwork period between two consecutive workdays and thus a critical recovery window for restoring psychophysiological systems before returning to work. Circadian effects should not be neglected when investigating evening recovery (Meijman & Mulder, 1998; Zijlstra et al., 2014) as they have a particularly high influence on psychophysiological states at this time of the day (Coumel et al., 1994; Hülsheger, 2016). To provide a comprehensive picture of the evening recovery process from job strain, we investigate subjectively perceived psychological recovery (fatigue) and objectively measured physiological recovery (HRV) after work (Ganster & Rosen, 2013) taking into account circadian effects.

Psychological Recovery. To address subjectively perceived psychological recovery, we focus on fatigue as an indicator of depleted energy (Meijman & Mulder, 1998). According to the ERM, fatigue represents reduced "work capacity and the willingness to perform" (Meijman & Mulder, 1998, p. 16). Sonnentag et al. (2008) define fatigue as low-arousal negative affective state similar to exhaustion and tiredness.

According to the ERM (Meijman & Mulder, 1998), high fatigue is expected at the end of work after investing energy in dealing with job stressors. Indeed, previous research has shown positive day-level associations between workload and evening fatigue (Keller & Meier, 2024). After the end of work, the ERM predicts decreasing fatigue as energy resources are replenished (Meijman & Mulder, 1998). In line with these assumptions, meta-analytic findings demonstrated negative associations between recovery and fatigue (Bennett et al., 2018).

However, also driven by circadian rhythms, as already mentioned above, fatigue typically increases as bedtime approaches (Hülsheger, 2016). Thus, we expect that the initial recovery-driven decline in fatigue after work will gradually wane later in the evening until it is eventually outweighed by the circadian-driven increase in fatigue. For example, previous findings indicate an energy decrease (Kosenkranius et al., 2023) and a fatigue increase towards bedtime in employee samples (Hülsheger, 2016). Integrating the assumptions of the ERM (Meijman & Mulder, 1998) with the aforementioned empirical findings on circadian influences, we hypothesize an initial decrease in fatigue after the end of work, reflecting recovery from job stressor exposure, followed by a subsequent increase in fatigue due to circadian rhythms before going to sleep:

H1: Fatigue follows a quadratic U-shaped trajectory in the evening after work.

Physiological Recovery. We focus on HRV as physiological recovery indicator, as HRV indicates psychophysiological adaptation such as recovery-related changes after stressful situations (Järvelin-Pasanen et al., 2018; Laborde et al., 2017). HRV refers to variations in the time intervals between consecutive heart beats (Del Reyes Paso et al., 2013; Laborde et al., 2017; Malik et al., 1996; J. F. Thayer & Lane, 2000), validly reflecting sympathetic and parasympathetic functions of the autonomic nervous system (Acharya et al., 2006). In stressful situations, a more regular heartbeat, thus reduced HRV, reflects predominantly sympathetic modulation of the heartbeat (Berntson et al., 1997; Tarvainen et al., 2014). In contrast, during recovery periods, high HRV indicates predominantly parasympathetic modulation of the heartbeat (Tarvainen et al., 2014). Thus, increasing HRV objectively indicates physiological recovery (Igboanugo & Mielke, 2023).

In line with the ERM (Meijman & Mulder, 1998) and the ALM (McEwen, 1998), parasympathetic HRV indicators, such as the square root of the mean squared differences of successive NN intervals (RMSSD), have been shown to decrease during periods of acute mental stress, including the occupational context (Castaldo et al., 2015; Järvelin-Pasanen et al., 2018). Hence, as employees are facing job stressors at work, HRV is expected to be relatively low at the end of the workday (McEwen, 1998; Meijman & Mulder, 1998). In contrast, during recovery periods, HRV should typically increase as physiological responses to job stressors diminish (McEwen, 1998; Meijman & Mulder, 1998). Indeed, over the course of a workday, Baethge et al. (2020) observed an inverted U-shaped RMSSD trajectory characterized by a temporary increase during the lunch break and low levels of HRV at the end of work.

However, HRV has been found to not only adapt in reaction to acute stressors (e.g., job stressors), but is also known to be affected by circadian adaptation (Baethge et al., 2020). Previous research has shown that HRV—due to circadian rhythms—typically follows a quadratic trajectory in the evening with a short initial decrease in HRV in the early evening followed by a long increase in HRV until early morning hours (Coumel et al., 1994). As the workday can be interpreted as a socially related Zeitgeber (Baethge et al., 2020)—an “external cue[] that synchronize[s] the biological clock with the environment” (Hülsheger, 2016, p. 907)—we assume a similar trajectory representing physiological adaptation following the end of the workday (scheduled in the early evening). Specifically, we hypothesize a short initial fading short-term decrease in HRV, introducing the turning point from the waning of initial sympathetic dominance at the end of work (Baethge et al., 2020) to increasing recovery and circadian-driven parasympathetic dominance, reflected in an ascending increase in HRV:

H2: HRV follows a U-shaped quadratic trajectory in the evening after work.

Next-Morning Recovery Outcomes

Meijman and Mulder (1998) highlight in the ERM that quantitatively and qualitatively ‘sufficient’ evening recovery is critical for employee functioning—especially next morning energy (willingness to perform) and cognitive functioning (capacity to perform)—and thus for job performance. They argue that both energy and cognitive functioning vary as a function of prior psychophysiological strain and recovery: leaving work highly strained and recovering poorly after work is expected to impair next-morning functioning, whereas effective recovery from high strain should restore employee functioning (Meijman & Mulder, 1998). Accordingly, we selected energy and cognitive functioning as next-morning recovery outcomes reflecting employees’ work potential (Meijman & Mulder, 1998).

Morning energy refers to a feeling of liveliness in the morning (Weigelt et al., 2022) that can be subjectively experienced as enthusiasm, vigor, or vitality (Quinn et al., 2012). Supporting the assumption that morning energy is sensitive to evening recovery effects, in previous research, evening recovery mechanisms such as relaxation or psychological detachment were positively associated with next-morning energy (Parker et al., 2020; Sonnentag et al., 2008). Zijlstra et al. (2014) highlight energy as crucial indicator of the willingness to perform in the sense of exerting effort to complete work-related tasks.

Morning cognitive functioning, in turn, refers to the capacity to suppress irrelevant impulses and stimuli, allowing individuals to focus on task-relevant processing (Engle et al., 1995; J. F. Thayer et al., 2009). This capacity is considered critical for effective adaptation and self-regulation in modern complex environments (Engle et al., 1995; J. F. Thayer et al., 2009), particularly at work, and can therefore be interpreted as the capacity to perform at work (Meijman & Mulder, 1998). While experience sampling studies with cognitive functioning outcomes are rare, two systematic reviews of cross-sectional and longitudinal studies highlight recovery as a critical prerequisite of cognitive functioning, particularly executive functioning such as cognitive inhibition (e.g., Forte et al., 2019; Nicolini et al., 2024). According to Meijman and Mulder (1998), impairments in cognitive functioning following 'insufficient' recovery manifest in reduced mental efficiency, either reflected by reduced performance outcomes (e.g., number of errors in a cognitive task) or by increased cognitive effort invested to maintain performance. Accordingly, we focus on cognitive functioning in the sense of efficient cognitive inhibition, indicated by a small number of inhibition errors capturing inhibitory success (i.e., cognitive performance) and a low response style variability capturing the associated costs (i.e., cognitive effort) in a Go–NoGo task (Bellgrove et al., 2004; Johnson et al., 2007; Manly et al., 2003).

Both energy and cognitive functioning are critical prerequisites for maintaining healthy and effective functioning at work, determining the degree to which employees are willing and able to invest effort to perform at work (Meijman & Mulder, 1998). In practical terms, on days when employees are well-recovered reporting high levels of energy and demonstrating high cognitive functioning in the morning (i.e., a small number of inhibition errors, low response style variability), they are probably better equipped to meet job stressors at work, eventually leading to improved job performance (Binnewies et al., 2009). Conversely, when employees start the workday with low energy levels and impaired cognitive functioning (i.e., a large number of inhibition errors, high response style variability), they may struggle to meet job stressors effectively. For example, in a previous study, available energy measured at noon significantly predicted increased attention to work, absorption, and effort in the afternoon (Weigelt et al., 2022). Furthermore, inhibitory processes are essential for a wide range of everyday and work-related tasks requiring executive functions including working memory, response inhibition, and emotion regulation (J. F. Thayer et al., 2009).

Effective Evening Recovery and Next-Morning Functioning

The evening recovery process can vary from day to day. While some evenings may be characterized by immediate and strong recovery onset (i.e., effective recovery), others may be characterized by sustained allostatic activation, slow unwinding processes, or incomplete recovery after work (Geurts & Sonnentag, 2006; R. S. Grant et al., 2026). According to the ERM (Meijman & Mulder, 1998), evening recovery is ‘sufficient’ if it restores employee functioning (energy, cognitive functioning). Hence, the effectiveness of previous evening recovery should be reflected in the extent to which evening recovery (i.e., slopes of the evening recovery trajectory) accounts for the variance in next-morning employee functioning beyond the residual effects of workday strain (i.e., intercept of the evening recovery trajectory; Miriam Arnold et al., 2023). After evenings characterized by effective recovery after work, employees are expected to exhibit higher levels of energy and cognitive functioning (e.g., high cognitive performance, low cognitive effort) the next morning (Meijman & Mulder, 1998). In contrast, after evenings characterized by ‘insufficient’ recovery after work, energy levels should be lower and cognitive performance should decrease or be linked to additional, compensatory cognitive effort (Meijman & Mulder, 1998). However, beyond referring to complete recovery, the ERM (Meijman & Mulder, 1998) does not specify what constitutes ‘sufficient’ (i.e., effective) recovery processes, for example, in terms of temporal characteristics.

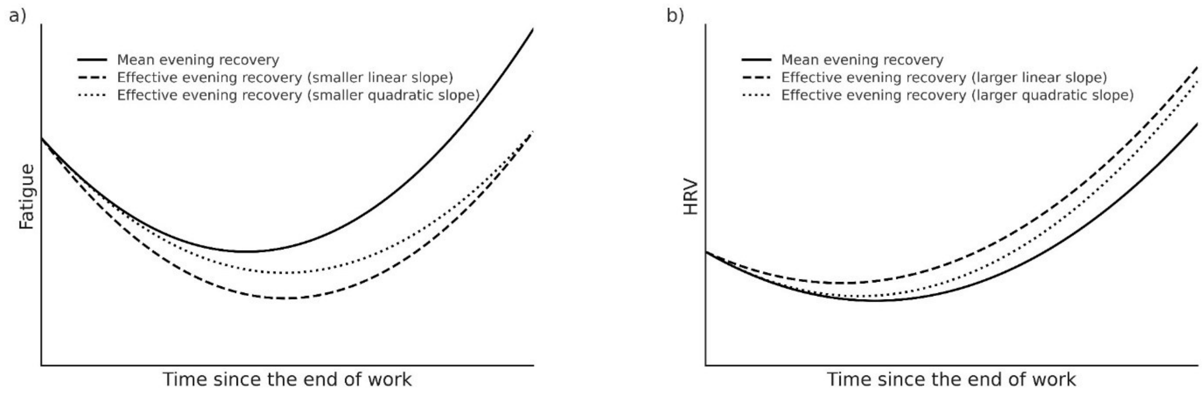
According to the ALM (McEwen, 1998), effective recovery means that allostatic stress responses end directly after the end of stressor confrontation instead of showing a prolonged stress response. Hence, applied to the occupational context, allostatic stress responses should cease promptly at the end of the workday—marking the end of exposure to job stressors—yielding an immediate and fast recovery onset (McEwen, 1998). These assumptions are supported by initial research on linear trajectories of evening recovery experiences demonstrating the advantage of immediate and fast compared to delayed and slow recovery for next-day well-being and performance (Maike Arnold et al., 2023; R. S. Grant et al., 2026).

Wrapping up the theoretical assumptions and empirical results, effective recovery trajectories should optimally be characterized by immediate, fast, and complete recovery (Geurts & Sonnentag, 2006), thereby optimizing the evening recovery period (Baethge et al., 2020). Taking into account the interplay of recovery and circadian effects, effective recovery trajectories may differ for the assumed psychological and physiological quadratic evening recovery trajectories.

We investigate recovery trajectories after the end of work, with x-values ≥0 representing time in hours since work ended (with zero marking the end of work) and y-values ≥0 representing fatigue and HRV. Accordingly, for the assumed recovery trajectories to be U-shaped, they should generally exhibit a positive intercept, a negative linear slope, and a positive quadratic slope. While the intercept of the evening recovery trajectory reflects employees' state at the end of the workday, the slopes capture temporal characteristics of the evening recovery process after work. A smaller (i.e., more negative) linear slope is associated with a later and lower minimum of the U-shaped trajectory (see Figure 4.1). Likewise, a smaller quadratic slope results in a later and lower minimum and a flatter (less curved) trajectory.

Figure 4.1

Hypothetical Effective a) Psychological and b) Physiological Evening Recovery Trajectories



Note. The figure was created with the help of ChatGPT (OpenAI, 2025). HRV = heart rate variability.

Psychological Recovery. With respect to the U-shaped subjective evening recovery trajectory, an effective recovery process should be characterized by a prolonged initial decrease in fatigue before circadian effects set in. The later and lower the turning point from a declining to an increasing trajectory, the larger the reduction in fatigue relative to the initial state at the end of the workday (i.e., the intercept of the evening recovery trajectory) and the more complete the recovery achieved before circadian effects set in. Accordingly, a lower minimum in fatigue reflects a more complete recovery process as highlighted in the ERM (Meijman & Mulder, 1998) whereas a later minimum indicates a longer recovery period that maximizes the quantitative aspects of the recovery process before the onset of circadian effects (Baethge et al., 2020; Meijman & Mulder, 1998). Consequently, U-shaped evening fatigue trajectories with later and lower minima indicate more complete and thus more effective recovery (Geurts & Sonnentag, 2006; Meijman & Mulder, 1998).

U-shaped trajectories with later and lower turning points from a declining to an increasing phase are characterized by either a smaller linear or a smaller quadratic slope, assuming all other parameters remain constant (see Figure 4.1a). Accordingly, U-shaped fatigue trajectories with smaller linear or quadratic slopes should indicate more effective evening recovery, and in turn, be positively associated with next-morning functioning (see Figure 4.2):

H3: The linear slope of the fatigue trajectory in the evening after work is negatively associated with energy (H3a) and cognitive performance (H3b) and positively associated with cognitive effort (H3c) at the beginning of the following workday.

H4: The quadratic slope of the fatigue trajectory in the evening after work is negatively associated with energy (H4a) and cognitive performance (H4b) and positively associated with cognitive effort (H4c) at the beginning of the following workday.

Physiological Recovery. An effective U-shaped physiological evening recovery trajectory should be characterized by an early and steep increase in HRV after work. An early and steep increase in HRV indicates timely and fast allostatic adaptation as highlighted in the ALM (McEwen, 1998), thereby maximizing quantitative and qualitative recovery across the evening allowing for a faster return to baseline levels (Meijman & Mulder, 1998). The earlier the turning point from a declining to an increasing trajectory, the shorter the adaptation period after the end of work (i.e., the end of job stressor confrontation) and the smaller the risk of prolonged allostatic adaptation (McEwen, 1998), representing more immediate and faster, hence effective, recovery (Geurts & Sonnentag, 2006).

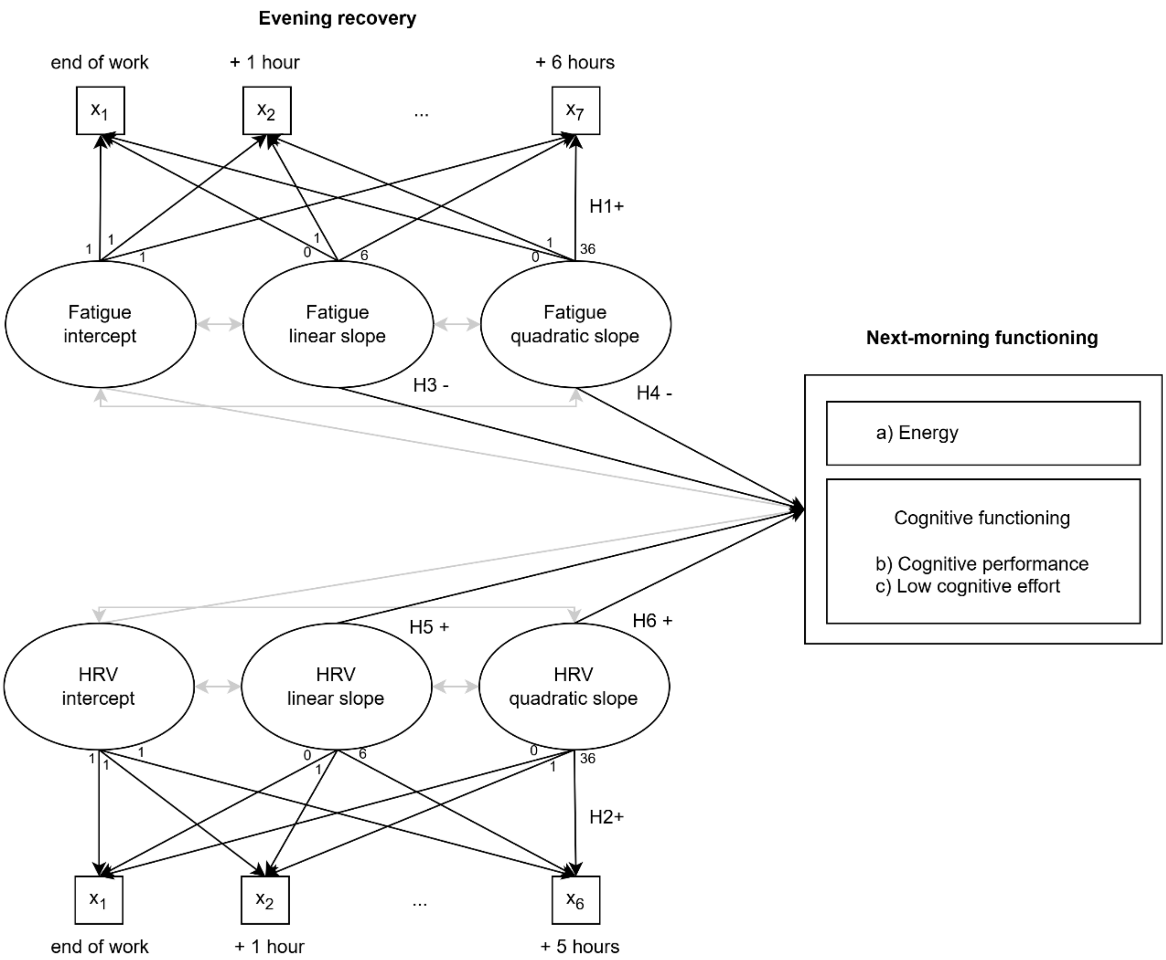
U-shaped trajectories with earlier turning points from a descending to an ascending trajectory are characterized by larger linear or quadratic slopes, assuming all other parameters remain constant (see Figure 4.1b). In particular, a larger quadratic slope results in a sharper bend of the trajectory, reflecting faster physiological recovery after the initial adaptation. Therefore, U-shaped physiological recovery trajectories with larger linear or quadratic slopes should represent more effective physiological evening recovery processes and, consequently, should be positively associated with next-morning functioning (see Figure 4.2):

H5: The linear slope of the HRV trajectory in the evening after work is positively associated with energy (H5a) and cognitive performance (H5b) and negatively associated with cognitive effort (H5c) at the beginning of the following workday.

H6: The quadratic slope of the HRV trajectory in the evening after work is positively associated with energy (H6a) and cognitive performance (H6b) and negatively associated with cognitive effort (H6c) at the beginning of the following workday.

Figure 4.2

Conceptual Model With Hypotheses



Note. Grey lines represent covariances between the intercepts and slopes of the same latent variable. x = momentary state measurement of the corresponding latent variable; H = hypothesis; HRV = heart rate variability.

Method

Sample and Procedure

A total of 65 German employees participated in our experience sampling study involving repeated hourly questionnaires on three evenings after work and a single questionnaire as well as a cognitive performance test on four consecutive mornings before work. Additionally, participants wore a chest belt with a continuously recording electrocardiogram (ECG) and activity sensor throughout the 72-hour study period. The study was part of a larger research project, including additional measurements every two hours at work. A three-day study duration was chosen, as recommended by Ganster and Rosen (2013), to balance reliable measurement of typical evening recovery trajectories with participant burden. We ensured availability of study materials and data quality by personal handover and face-to-face introductions. Project members approached eligible individuals from their private and professional networks, and the study was advertised both online (university website, social media platforms) and by flyers distributed in public buildings. Data were collected from March to September 2023. Employees volunteered for the study by signing up via e-mail. To ensure anonymity, study smartphones, sensors, and chest belts were distributed in randomly assigned envelopes labeled with pseudonyms.

One day before their individual experience sampling period began, participants were asked to complete an initial 10-minute smartphone questionnaire covering demographic variables and a trial version of the cognitive performance test. They were instructed to begin wearing the chest belt with attached sensor on the morning of the first study day, after waking but before commuting to work, and to continue wearing it for 72 hours, allowing for short breaks for hygiene purposes.

During the three-day study period, participants were instructed to complete a daily end-of-work questionnaire by manually pressing the respective button on their study smartphone before leaving work. Subsequently, a smartphone alarm reminded participants every hour to complete an evening questionnaire. This sequence continued until participants manually completed a bedtime questionnaire before going to sleep, ending the series of evening assessments. We implemented one-hour intervals between evening questionnaires, as recommended by D. M. Fisher et al. (2019), as this interval is deemed short enough to capture a sufficient number of assessments between the end of the workday and bedtime to accurately model fine grained recovery trajectories. At the same time, the interval is deemed long enough to avoid overburdening participants or disrupting typical evening recovery activities. Additionally, on each of the four mornings during the 72-hour study period, participants were asked to complete a situational smartphone questionnaire concluding with the cognitive performance test shortly before starting work. This timing was chosen, as it marks the end of the recovery period and the onset of potentially new psychophysiological responses to job stressors (D. M. Fisher et al., 2019).

The inclusion criteria for participation in our study required individuals to be of legal age and work for at least six hours per day for a minimum of three days during the study week. Shift workers were excluded to minimize the potential influences of varying day-night-rhythms on recovery patterns. The sample consisted of 40 women and 24 men, with a mean age of 35.56 years (*SD* = 13.27, *Range* = 19–62; one participant did not provide demographic information). Participants had an average tenure of 7.27 years in their current organization (*SD* = 10.15, *Range* = 0–41) and a mean of 10.71 years of overall professional experience (*SD* = 12.98, *Range* = 0–44; data of one participant was excluded due to implausible values). Participants worked in diverse professional areas, with 15 participants working in industry, 9 in administration, 6 in research, and the remainder in fields such as education, care, and counselling. Leadership responsibilities were reported by 21 participants. Additionally, 23 participants were engaged in ongoing professional or educational training. Participants worked an average of 34.80 hours per week as per their contracts (*SD* = 7.84; *Range* = 13–45) and reported an average of 4.56 weekly overtime hours (*SD* = 5.77; *Range* = 0–30).

In total, participants completed 1,287 situational questionnaires. We did not exclude data if participants responded to questionnaires on additional days beyond the designated study period. However, to maintain consistent time lags, we excluded data from questionnaires that deviated by more than 20 minutes from the intended 1-hour interval between evening measurements. This filtering process resulted in 1,263 valid situational questionnaires, collected across 200 evenings and 185 subsequent mornings. On average, participants started the first evening questionnaire at 5:18 p.m. (*SD* = 1.65 hours), consistent with typical end-of-work times in Germany.

The study's ethical aspects were reviewed and approved by the local ethics committee (approval no. and institute blinded for peer review). Informed consent was obtained from all participants through signed written documentation. As compensation, participants received a 30€ incentive and their individual 72-hour HRV profile, which was distributed in sealed envelopes labeled with participant pseudonyms to ensure anonymity. Participants were informed that the HRV profiles provided are based on ECG data collected for scientific purposes and should therefore not be interpreted as medical diagnostic criteria.

Measures

All items were presented in the movisensXS application (movisens GmbH, Karlsruhe, Germany) on Android 11.0 Nokia G50 Smartphones with 6.82" HD displays (1640 x 720 pixels). If not indicated differently, all self-report items were measured with a seven-point Likert scale ranging from 0 = *does not apply at all* to 6 = *fully applies*. Within-person reliability estimates were calculated based on the number of items, within-person variance, and residual variance as recommended by Bonito et al. (2012).

Psychological Recovery. We measured fatigue with four adapted items of the short screening version (Petrowski et al., 2021) of the German Profile of Mood States (Albani et al., 2005; McNair et al., 1971). A sample item is "At the moment, I feel exhausted". Within-person reliability ranged between .71 and .81 across the three study days.

Physiological Recovery. We recorded physiological recovery through ECG signals with movisens EcgMove 3 and EcgMove 4 sensors with an output rate of 1,024 Hz (movisens GmbH, Karlsruhe, Germany). As HRV indicator, we chose RMSSD, the most common time-domain HRV measure (Del Reyes Paso et al., 2013; Forte et al., 2019; Laborde et al., 2017; Malik et al., 1996; Shaffer & Ginsberg, 2017). RMSSD is considered to be hardly influenced by respiratory frequency (Hill et al., 2009; Laborde et al., 2017) and one of the most robust indicators of parasympathetic activity (Laborde et al., 2017; Malik et al., 1996).

Next-Morning Energy. We measured next-morning energy with the pictorial seven-point energy scale of Weigelt et al. (2022) represented by pictures ranging from a red empty battery (0) to a green fully charged battery (6). Due to its user-friendly experience, this scale is especially feasible for repeated assessments (Weigelt et al., 2022).

Next-Morning Cognitive Functioning. To measure cognitive functioning, we presented the 90-second smartphone-based Sustained Attention to Response Task (SART; Robertson et al., 1997), provided online by Perzl et al. (2024), within the movisensXS application using Presentation® software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com). In this Go–NoGo task, the digits from 1–9 were randomly presented for 250ms in the middle of the screen, and each trial was followed by a black screen for 900ms. Participants were asked to quickly touch the screen whenever a new digit appears (1, 2 or 4–9; Go trial), unless the 3 appears (NoGo trial). Capturing both cognitive performance and related cognitive effort (Bellgrove et al., 2004), we recorded the number of commission errors (i.e., touching the screen during the NoGo trial) and the standard deviation of reaction times in Go trials (SD_{RT}). Commission errors represent inhibition errors, with a lower number of errors indicating better cognitive performance. SD_{RT} provides information about the variability of the response style, with a high variability indicating high cognitive effort (Bellgrove et al., 2004). Both cognitive functioning outcomes can be interpreted as indicators of controlled attention and successful response inhibition (Bellgrove et al., 2004;

Johnson et al., 2007; Manly et al., 2003)—cognitive domains that were significantly associated with parasympathetic activation in previous studies (Forte et al., 2019; Ottaviani et al., 2019).

Highlighting its feasibility for occupational field research, in previous studies, SART performance was sensitive to stress and recovery (Perzl et al., 2024; Shields et al., 2016), and allowed to depict recovery effects after interventions such as nature walks (Pasanen et al., 2018), live-streaming lunch break activity and relaxation exercises (Riedl et al., 2023), and mindfulness meditation (Riedl et al., 2024). In addition, SART performance is significantly associated with job performance (Wilson et al., 2018) as well as general cognitive failures (Smilek et al., 2010), especially with the subscales attention, distractibility, and false triggering (Schepers et al., 2023). Furthermore, both job stressors and the SART require cognitive effort, especially in situations with suboptimal psychophysiological states (Bellgrove et al., 2004; Meijman & Mulder, 1998).

Control Variables. As recommended by Laborde et al. (2017), we collected accelerometer data in parallel to the ECG recordings to control for bodily movement. Furthermore, participants reported their age, gender, and body mass index (BMI) in the initial questionnaire, as these are well-known covariates of HRV (Massaro & Pecchia, 2019). To monitor technical issues and interruptions during completion of the cognitive performance task, the SART was followed by the two dichotomous (yes/no) control variables "During task completion, technical problems occurred" and "During task completion, I was interrupted".

Data Analysis

Before analyzing the data, we visually inspected the 72-hour ECG signals of all participants and excluded the ECG data of 19 participants due to massive artifacts. The ECG data of the remaining 46 participants had a high mean valid measurement proportion of 85.78%. We further excluded artifacts in the remaining ECG data with a filter recommended by Clifford et al. (2002) using the movisens DataAnalyzer (movisens GmbH, Karlsruhe, Germany). In particular, based on R-peaks detected with a procedure similar to the approach of Hamilton (2002), inter-beat intervals below 250ms and above 2000ms and R-peak amplitudes below 0.1mV and above 5mV were removed. We also used the movisens DataAnalyzer (movisens GmbH, Karlsruhe, Germany) with a bandpass filter for each axis (0.25–11 Hz) to calculate the mean three axes acceleration as an indicator of bodily movement and RMSSD as HRV indicator. Matching self-reported and sensor data, we extracted the 5-minute means of RMSSD and bodily movement (Malik et al., 1996) prior to each situational questionnaire. Only 5-minute HRV means consisting of five valid 1-minute assessments remained in the data set, resulting in 746 valid HRV measurements of 40 participants. As the 5-minute segments of RMSSD were non-normally distributed, we log transformed the data (ln) prior to further analyses (Laborde et al., 2017).

As participants were asked to respond to smartphone-based questionnaires every hour in between the end of the workday and bedtime, we had a large variety of valid measurement time points per evening (0–13). To retain as many data points as possible and to depict a time period similar to a typical evening, we decided to choose the maximum measurement duration which ensures that each measurement time point provides an acceptable number of valid questionnaires.

For psychological recovery, we focused on the first seven evening questionnaires, which correspond to the mean number of completed questionnaires per evening (M = 6.76, SD = 1.96) and account for 89.84% of all evening questionnaires. These seven questionnaires span approximately six hours after the end of work, representing a typical evening duration before bedtime (e.g., from 5 p.m. to 11 p.m.), and aligning with evening durations reported in previous research (Maike Arnold et al., 2023). Each of these seven measurements was completed on 97–192 evenings (49–96%), whereas the six excluded later measurement time points were completed on fewer than 30% (1–59) of evenings. Excluding these rare late evening measurements also avoids artificial data points, as most employees were already asleep after the seventh assessment on 63% of study evenings. Overall, our final data set included 911 fatigue assessments, nested in 200 evenings, nested in 65 participants, with covariance coverage ranging from .32 to .68.

Due to technological issues and rigorous artifact exclusion, the dataset for physiological recovery measurements was substantially smaller. To ensure a sufficient number of observations at each time point, we restricted the analysis to the first six measurement occasions temporarily aligning with the self-reports. These six time points span the first five hours after work and account for 81.10% of valid evening HRV measurements. At each time point, we recorded 79–108 (40–54%) valid state HRV measurements, whereas we excluded later time points with less than 32% (0–63) valid measurements, analogous to the approach used for the subjective recovery indicators. As our primary focus was recovery after the end of work rather than circadian effects, which primarily determine psychophysiological processes later in the evening, this approach provides a reasonable basis for estimating reliable recovery trajectory estimates. Overall, our final data set covered 474 HRV state assessments nested in 98 evenings nested in 39 participants. For the HRV data, covariance coverage varied between 0.65 and 0.77.

To ensure valid cognitive functioning measurements, 9 of the 234 situational cognitive morning assessments were excluded from analysis due to reported technical issues. Additionally, 41 cognitive assessments were removed because participants indicated interruptions during task completion, resulting in a total of 184 valid cognitive functioning assessments.

Momentary, day-level, and person-level correlations were calculated with three-level models using Mplus version 8.11 (Muthén & Muthén, 2024). Due to the very small cluster size of three evenings per participant, we modeled the recovery trajectories in the evening after the end of work with separate latent growth curve models applying TYPE = COMPLEX in Mplus version 8.11 and full information maximum likelihood estimation (McNeish, 2014;

McNeish et al., 2017; Muthén & Muthén, 2024)—similar to the approach taken by Baethge et al. (2020; see Figure 4.2). TYPE = COMPLEX allowed us to analyze 200 (fatigue) and 98 (HRV) evenings, respectively, taking into account the non-independence of observations by correcting standard errors and fit indices. For HRV, we controlled for typical covariates including the time-invariant covariates age (grand-mean centered), BMI (grand-mean centered), and gender as predictors of intercept and slopes as well as the time-varying covariate bodily movement (person-mean centered) as predictor of HRV measured at the respective time point. Similar to Baethge et al. (2020), we excluded nonsignificant ($p > .10$) control variables consecutively to keep the models as simple as possible.

Finally, we used latent growth parameters as predictors of next-morning energy and cognitive functioning in path models (see Figure 4.2). For these path models, we applied numerical integration (ALGORITHM = INTEGRATION) to allow for robust model estimation despite using latent factors as predictors of differently scaled outcomes (energy, cognitive performance, cognitive effort). Therefore, no model fit indices can be reported for these models.

Transparency and Openness

We describe our sampling plan, all data exclusions, all manipulations, and all measures in the study. The analysis code is available on OSF (https://osf.io/cfsre/?view_only=2bc66160da6d4637b78f478727385f34). The datasets generated and analyzed during the current study are available from the corresponding author on request. This study's design and its analysis were not preregistered. Generative artificial intelligence (ChatGPT; OpenAI, 2025) was not used in this research except for editing purposes (i.e., checking grammar, wording, and writing style) and visualization purposes (as cited in Figure 4.1 and Figure 4.3).

Results

Descriptive Analyses

Intraclass correlations as well as momentary, day-level, and person-level correlations of all study variables are reported in Table 4.1. We observed the full-scale range (0–6) for all self-report items. Similarly, observed inhibition errors ranged from 0 to 8, which is identical to the full range of possible inhibition errors in the SART.

Evening Recovery Trajectories

In line with Hypothesis 1, for fatigue, the quadratic growth model yielded a significant quadratic slope ($\lambda_{quad.slope}$ = 0.46, 95 % CI [0.13, 0.78], p = .006; see Table 4.2), but no significant linear slope ($\lambda_{lin.slope}$ = -0.17, 95 % CI [-0.45, 0.10], p = .215), indicating a U-shaped trajectory of fatigue in the evening after work (see Figure 4.3a). The intercept significantly negatively covaried with the linear slope (β = -0.31, 95 % CI [-0.61, -0.01], p = .043) and the linear slope negatively covaried significantly with the quadratic slope (β = -0.93, 95 % CI [-0.99, -0.87], p < .001). No significant covariances were shown between the intercept and the quadratic slope (β = 0.18, 95 % CI [-0.15, 0.51], p = .289).

Supporting Hypothesis 2, we identified a quadratic U-shaped HRV trajectory (see Figure 4.3b) with a significant quadratic ($\lambda_{quad.slope}$ = 0.42, 95 % CI [0.11, 0.72], p = .007), but not linear slope ($\lambda_{lin.slope}$ = -0.34, 95 % CI [-0.77, 0.08], p = .113; see Table 4.2). Covariances were significant between the linear and quadratic slope (β = -0.93, 95 % CI [-1.00, -0.86], p < .001), but not between the intercept and the linear slope (β = 0.25, 95 % CI [-1.28, 1.78], p = .750) and the intercept and the quadratic slope (β = -0.23, 95 % CI [-1.31, 0.85], p = .674).

Table 4.1

Three-Level Correlations Among Study Variables and Descriptive Statistics of Study Variables

Variable	*ICC*	*M*	*SD*	1	2	3	4	5	6	7	8
Momentary level											
1. Fatigue		2.31	2.15								
2. HRV		3.31	0.38	.12*							
3. Bodily movement		0.06	0.01	-.07	-.51**						
Day-level											
1. Fatigue	.21										
2. HRV	.08			-.25							
3. Bodily movement				-.13	-.47						
4. Morning energy		4.18	1.18	.10	.06	-.05					
5. Morning inhibition errors		2.88	3.67	.07	.03	-.02	-.25*				
6. Morning response style variability		76.56	2155.44	-.05	-.02	.11	-.07	.14			
Person-level											
1. Fatigue	.45										
2. HRV	.49			-.09							
3. Bodily movement				-.44*	.34*						
4. Morning energy	.46			-.39*	-.03	-.09					
5. Morning inhibition errors	.45			.31	.19	.34	-.15				
6. Morning response style variability	.49			-.03	-.20	-.27	.14	.49*			
7. Age		35.56	13.27	-.20	-.50**	-.23	.15	-.49**	-.01		
8. BMI		23.72	4.30	-.12	-.37*	-.08	.21	-.20	-.11	.19	
9. Gender				-.05	-.17	-.06	.11	-.21	-.15	.12	.27*

Note. Standardized correlation estimates are reported. *ICC* = intraclass correlation; *M* = mean; *SD* = standard deviation; HRV = Heart Rate Variability measured by the square root of the mean squared differences of successive NN intervals; BMI = body mass index.

**p* < .05; ***p* < .01.

Table 4.2

Parameter Estimates for the Linear Growth Curve Models of Fatigue and HRV

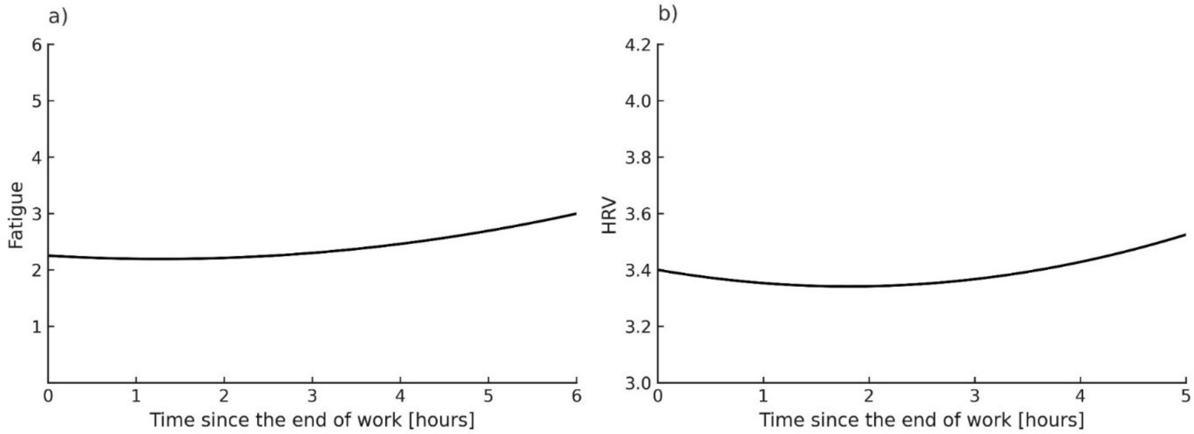
	Fatigue		HRV	
	β (*SE*)	95% CI	β (*SE*)	95% CI
Fixed effects				
Mean of intercept	1.709 (0.172)**	[1.372, 2.047]	7.619 (1.091)**	[5.482, 9.757]
Mean of linear slope	-0.173 (0.139)	[-0.446, 0.100]	-0.342 (0.216)	[-0.765, 0.081]
Mean of quadratic slope	0.459 (0.166)**	[0.133, 0.784]	0.415 (0.154)**	[0.113, 0.716]
Time-invariant control variables on intercept				
Age			-0.634 (0.137)**	[-0.903, -0.366]
BMI			-0.296 (0.179)	[-0.647, 0.054]
Time-variant control variables on momentary HRV				
Bodily movement T0			-0.307 (0.080)**	[-0.463, -0.151]
Bodily movement T1			-0.284 (0.105)**	[-0.491, -0.078]
Bodily movement T2			-0.267 (0.074)**	[-0.413, -0.121]
Bodily movement T4			-0.246 (0.132)	[-0.504, -0.012]
Bodily movement T5			-0.242 (0.073)**	[-0.385, -0.099]
Model fit indices				
$\chi 2$ (*df*)	471.887* (57)		49.206** (19)	
CFI	.944		.937	
RMSEA	.071		.089	
SRMR	.084		.065	

Note. $N_{fatigue}$ = 200, N_{HRV} = 98. We only report significant control variables ($p < .10$), nonsignificant covariates were removed stepwise to build parsimonious models. HRV = heart rate variability measured by the square root of the mean squared differences of successive NN intervals; β = standardized estimate; *SE* = standard error; 95% CI = 95% confidence interval; BMI = body mass index. CFI = comparative fit index; RMSEA = root mean square error of approximation; SRMR = standardized root mean square residual.

$^{**}p < .01$, $^{*}p < .05$.

Figure 4.3

Evening a) Psychological and b) Physiological Recovery Trajectories



Note. Trajectories were modeled with unstandardized estimates. The figure was created with the help of ChatGPT (OpenAI, 2025). HRV = heart rate variability.

Next-Morning Recovery Outcomes

Contradicting Hypotheses 3a and 4a, no significant associations were observed between slopes of the fatigue trajectory and next-morning energy ($\beta_{lin.slope}$ = 0.37, 95 % CI [-0.28, 1.01], p = .265; $\beta_{quad.slope}$ = 0.30, 95 % CI [-0.36, 0.97], p = .372; see Table 4.3). Hence, a smaller linear or quadratic slope of the fatigue trajectory (i.e., U-shaped fatigue trajectories with a later and lower minimum) was not associated with increased next-morning energy.

Not supporting Hypothesis 3b, the linear slope of the fatigue trajectory was unrelated to morning inhibition errors ($\beta_{lin.slope}$ = -0.48, 95 % CI [-1.13, 0.18], p = .152). However, in line with Hypothesis 3c, the linear slope was positively correlated with response style variability ($\beta_{lin.slope}$ = 0.72, 95 % CI [0.04, 1.40], p = .037). Thus, a smaller linear slope of the fatigue trajectory (i.e., U-shaped fatigue trajectories with a later and lower minimum) was not associated with better cognitive performance but with reduced cognitive effort.

Table 4.3

Results of Evening Fatigue Trajectory Characteristics Predicting Next-Morning Energy and Cognitive Functioning

	Morning energy		Morning inhibition errors		Morning response style variability	
	β (*SE*)	95% CI	β (*SE*)	95% CI	β (*SE*)	95% CI
Fixed effects	3.975 (0.372)**	[3.246, 4.705]	1.912 (0.333)**	[1.259, 2.564]	1.614 (0.292)**	[1.042, 2.185]
Random effects	0.942 (0.049)**	[0.845, 1.038]	0.902 (0.072)**	[0.761, 1.043]	0.807 (0.096)**	[0.620, 0.995]
Fatigue trajectory characteristics						
Intercept	-0.145 (0.104)	[-0.349, 0.059]	0.168 (0.112)	[-0.051, 0.386]	-0.002 (0.127)	[-0.251, 0.247]
Linear slope	0.365 (0.327)	[-0.277, 1.007]	-0.479 (0.334)	[-1.134, 0.176]	0.720 (0.345)*	[0.044, 1.396]
Quadratic slope	0.302 (0.339)	[-0.362, 0.967]	-0.807 (0.342)*	[-1.477, -0.136]	0.825 (0.329)*	[0.180, 1.470]

Note. $N = 201$. β = standardized estimate; *SE* = standard error; 95% CI = 95% confidence interval.

$^{**}p < .01$, $^{*}p < .05$.

Contrary to our expectations and contradicting Hypothesis 4b, the quadratic slope of the fatigue trajectory was negatively related to morning inhibition errors ($\beta_{quad.slope}$ = -0.81, 95 % CI [-1.48, -0.14], p = .018), thus positively associated with cognitive performance. In line with Hypothesis 4c, the quadratic slope was positively correlated with response style variability ($\beta_{quad.slope}$ = 0.83, 95 % CI [0.18, 1.47], p = .012). Hence, supporting our expectations, a smaller quadratic slope of the fatigue trajectory (i.e., U-shaped fatigue trajectories with a later and lower minimum) was associated with reduced cognitive effort but, contradicting our expectations, also related to cognitive performance decrements.

Contradicting Hypotheses 5a and 5b as well as 6a and 6b, none of the HRV trajectory slopes were significantly associated with next-morning energy ($\beta_{lin.slope}$ = 0.24, 95 % CI [-1.22, 1.70], p = .745; $\beta_{quad.slope}$ = 0.25, 95 % CI [-1.07, 1.56], p = .712; see Table 4.4) and next-morning inhibition errors ($\beta_{lin.slope}$ = 0.46, 95 % CI [-0.48, 1.40], p = .341; $\beta_{quad.slope}$ = 0.09, 95 % CI [-0.76, 0.94], p = .834). However, supporting Hypothesis 5c and 6c, linear and quadratic slopes of the HRV trajectory were negatively associated with next-morning response style variability in the SART ($\beta_{lin.slope}$ = -1.34, 95 % CI [-2.66, -0.01], p = .048; $\beta_{quad.slope}$ = -1.26, 95 % CI [-2.31, -0.22], p = .018). Hence, larger linear and quadratic slopes of the HRV trajectory (i.e., U-shaped HRV trajectories with an earlier increase) were unrelated to next-morning energy and cognitive performance but associated with reduced cognitive effort.

Despite in most cases reflecting the effects of the quadratic slopes, significant effects linked to linear slopes should be interpreted with caution as their means were not significant in the latent growth models for both recovery indicators (fatigue, HRV).

Table 4.4

Results of Evening HRV Trajectory Characteristics Predicting Next-Morning Energy and Cognitive Functioning

	Morning energy		Morning inhibition errors		Morning response style variability	
	β (*SE*)	95% CI	β (*SE*)	95% CI	β (*SE*)	95% CI
Fixed effects	4.122 (0.964)**	[2.232, 6.013]	0.268 (0.730)	[-1.163, 1.698]	2.131 (1.148)	[-0.119, 4.381]
Random effects	0.988 (0.060)**	[0.871, 1.105]	0.831 (0.130)**	[0.576, 1.085]	0.774 (0.213)**	[0.357, 1.191]
HRV trajectory characteristics						
Intercept	-0.053 (0.144)	[-0.335, 0.229]	0.213 (0.113)	[-0.008, 0.434]	0.021 (0.163)	[-0.299, 0.342]
Linear slope	0.242 (0.741)	[-1.217, 1.701]	0.457 (0.480)	[-0.484, 1.398]	-1.335 (0.674)*	[-2.656, -0.014]
Quadratic slope	0.247 (0.669)	[-1.065, 1.559]	0.091 (0.434)	[-0.760, 0.942]	-1.264 (0.535)*	[-2.314, -0.215]

Note. N = 134. All covariates reported in Table 2 were equally included in this model. HRV = heart rate variability measured by the square root of the mean squared differences of successive NN intervals; β = standardized estimate; *SE* = standard error; 95% CI = 95% confidence interval.

**p < .01, *p < .05.

Discussion

In this experience sampling study among employees, we investigated if and how psychological (fatigue) and physiological (HRV) recovery processes during the evening after work contribute to next-morning energy and cognitive functioning. Consistent with our hypotheses, latent growth curve models revealed U-shaped trajectories for both fatigue and HRV, indicating that recovery unfolded nonlinearly across the evening. On average, employees' psychological and physiological recovery trajectories showed an initial decrease, reached a turning point, and subsequently increased in line with circadian influences later in the evening. Contrary to our expectations, neither the linear nor the quadratic slopes of the fatigue or HRV trajectories were linked to next-morning energy. However, in line with our hypotheses, fatigue trajectories characterized by smaller linear slopes and HRV trajectories characterized by larger linear or quadratic slopes were associated with better next-morning cognitive functioning, particularly more effortless performance. Hence, evening trajectories characterized by more complete psychological and more immediate physiological recovery facilitated next-morning cognitive functioning, but not energy.

Theoretical Implications

Evening Recovery Processes. Our findings demonstrating quadratic trajectories of fatigue and HRV throughout the evening support the assumption that recovery is a process of changing psychophysiological states (Meijman & Mulder, 1998; Zijlstra et al., 2014) that—particularly during the evening recovery period—is affected by circadian effects (Zijlstra et al., 2014). By incorporating objectively measured physiological recovery (Sonnentag et al., 2017) and explicitly accounting for the interplay of recovery after the end of work and evening circadian effects (Zijlstra et al., 2014), our study extends previous research that has primarily investigated linear trajectories of self-reported evening recovery experiences (Maike Arnold et al., 2023; R. S. Grant et al., 2026) or circadian effects (Coumel et al., 1994; Hülsheger, 2016) in isolation.

The absence of a significant linear slope for the fatigue trajectory may be explained by our demanding study design, which may have resulted in a highly selective low-strain sample. Supporting this assumption, the intercept of the fatigue trajectory was relatively low and negatively covaried with its linear slope. Given that a simpler study design with fewer measurement time points may capture the essential information (e.g., by applying evening reconstruction methods; Maike Arnold et al., 2023; Kahneman et al., 2004) while minimizing participant burden and potential interruptions of natural recovery behaviors during the evening, a more parsimonious study with a broader and more diverse employee sample may provide more favorable conditions for detecting a larger average decrease in fatigue after the end of work.

The quadratic U-shaped HRV trajectory in the evening after work with an initial decrease followed by an increase later in the evening replicates the evening segment of the whole-day HRV pattern observed in a small sample of young army employees (Coumel et al., 1994). Furthermore, the present HRV trajectory reflects the physiological adaptation after the end of job stressor exposure (Ganster & Rosen, 2013) as conceptualized by the ALM (McEwen, 1998). By examining physiological adaptation after (job) stressor exposure in the evening after work, we extend previous empirical evidence focusing mainly on self-reported psychological recovery indicators (Steed et al., 2021) and we complement studies focusing primarily on physiological responses to workplace stressors (Baethge et al., 2020) and physiological recovery after standardized stressor exposure in a laboratory setting (Schilbach et al., 2021).

Overall, our curvilinear psychological and physiological recovery trajectories across the evening suggest that important information is missed when considering only mean or end-point recovery, or assuming linear change. In particular, the location and timing of the turning point from a descending to an ascending trajectory can inform about ‘sufficient’ or ‘insufficient’ recovery (Meijman & Mulder, 1998). For example, the location of the minimum of the fatigue trajectory (early and high vs. late and low) relative to a fixed intercept can provide critical information on the extent of recovery. Similarly, the location of the minimum of the HRV trajectory (early and high vs. late and low) can provide critical information regarding prolonged stress responses (McEwen, 1998) and the optimal use of the evening recovery period (Baethge et al., 2020).

Effective Evening Recovery and Next-Morning Cognitive Functioning. Refining ERM assumptions about 'quantitatively and qualitatively sufficient' recovery (Meijman & Mulder, 1998) and underscoring the importance of temporal aspects, the temporal characteristics of psychological and physiological evening recovery trajectories were linked to next-morning cognitive functioning (i.e., effortless performance). These findings enrich recovery research, which has largely focused on activities, experiences, and environments (instead of temporal characteristics) and self-reported recovery rather than objective, performance-related outcomes (Sonnentag et al., 2017). Furthermore, these results extend previous studies investigating the effects of linear psychological recovery processes on next-day self-reported outcomes (Maike Arnold et al., 2023; R. S. Grant et al., 2026). Different assumptions about 'sufficient' evening recovery (i.e., complete recovery for fatigue before the onset of opposing circadian effects vs. immediate physiological adaptation for HRV after the end of work) further highlight the need for a multi-modal assessment of evening recovery trajectories.

Psychological U-shaped recovery trajectories characterized by a lower and later minimum were associated with a lower response style variability in the SART, indicating reduced cognitive effort (Bellgrove et al., 2004). Given that the linear slope of the fatigue trajectory was also not significantly associated with changes in the number of inhibition errors (i.e., cognitive performance), these results suggest that evenings with a later and lower fatigue minimum are associated with more effortless cognitive performance the next morning, hence increased capacity to perform (Engle et al., 1995; J. F. Thayer et al., 2009). Conversely, evenings with an earlier and higher fatigue minimum, indicating a lower extent of recovery before the onset of circadian effects, were associated with increased compensatory cognitive effort to maintain cognitive performance. This result supports the ERM assumption that more complete recovery before the onset of bedtime fatigue—reflected in a later and lower minimum value of the U-shaped fatigue trajectory—constitutes ‘sufficient’ recovery (Meijman & Mulder, 1998). The fact that neither the average subjective evening recovery nor the momentary subjective recovery measured at bedtime capture the minimum of fatigue before the onset of circadian effects underscores the added value of adopting a process perspective when investigating recovery, particularly during recovery periods that are highly affected by circadian effects, such as the evening.

Results were less clear with regard to the quadratic slope of the fatigue trajectory. Despite being equally associated with reduced response style variability (i.e., reduced cognitive effort), a smaller quadratic slope was also associated with an increased number of inhibition errors (i.e., reduced cognitive performance)—contrary to our hypothesis. Because reduced cognitive effort in this case coincided with performance impairments, this pattern can neither be interpreted as cognitive functioning improvement (e.g., low mental effort for the same performance) nor impairment (e.g., reduced performance despite similar effort). Rather, this inconsistent pattern may reflect a motivational change (e.g., reducing performance standards; Meijman & Mulder, 1998).

Possibly, circadian influences can explain this unexpected result. In contrast to all other significant effects that showed consistent result patterns for linear and quadratic slopes, this unexpected effect for cognitive performance was only found for the quadratic, not for the linear slope of the fatigue trajectory, even though both determine the location of the trajectory’s minimum. The quadratic slope not only changes the location of the trajectory’s minimum to a lower and later value (similar to the linear slope) but also reduces the bending of the trajectory. The further away from the minimum, the larger the effect of the bend.

Therefore, in the case of the psychological recovery process, which is interrupted and reversed by circadian effects, these changes in the trajectory's bend might rather represent differences in circadian effects than in the actual evening recovery process. For example, a slower increase in fatigue before bedtime may be associated with reduced sleep time (Shochat et al., 2021), therefore affecting cognitive performance (i.e., inhibition errors) negatively. As we do not aim to declare variance in next-morning cognitive functioning with circadian predictors, the results linked to the quadratic slope of the fatigue trajectory should be interpreted with caution.

Physiological U-shaped recovery processes characterized by a higher minimum reached earlier in the evening (and potentially stronger bending) were generally unrelated to the number of inhibition errors (i.e., cognitive performance) but significantly associated with lower response style variability in the SART (i.e., reduced cognitive effort; Bellgrove et al., 2004), overall indicating effortless attention (Meijman & Mulder, 1998) and increased capacity to perform (Engle et al., 1995; J. F. Thayer et al., 2009). According to the ALM (McEwen, 1998), a higher and earlier HRV minimum (and potentially stronger bending of the HRV trajectory) signals a less severe prolonged physiological stress response after work and faster physiological adaptation to the nonwork environment. These two aspects align with key resilience characteristics: reduced impairments in health and well-being linked to stressor exposure and timely adaptation after stressor exposure (D. M. Fisher et al., 2019). Furthermore, these results extend previous findings on the sensitivity of central executive functions to physiological recovery found in cross-sectional (Forte et al., 2019) and longitudinal studies (Nicolini et al., 2024) to day-level associations (J. F. Thayer et al., 2009). Overall, these results support the assumption that an immediate and strong recovery onset characterizes effective physiological evening recovery processes (Geurts & Sonnentag, 2006; McEwen, 1998) and represents critical temporal evening recovery characteristics enhancing next-morning cognitive functioning, further refining the assumptions regarding 'sufficient qualitative and quantitative recovery' proposed by the ERM (Meijman & Mulder, 1998).

Our results on cognitive functioning indicate that associations between 'insufficient' evening recovery and next-morning cognitive effort occur straight away while cognitive performance is not immediately affected. A plausible explanation for these results may be found in compensatory effort processes (Hockey, 1993; Meijman & Mulder, 1998). After evenings characterized by insufficient recovery, employees may compensate for performance decrements in the SART (higher number of inhibition errors) by investing more cognitive effort in task completion (Meijman, 1997). However, as compensatory effort is linked to intense load reactions, performance decrements might not generally be avoided but rather become apparent later in the workday after renewed stressor confrontation (Meijman & Mulder, 1998).

Effective Evening Recovery and Next-Morning Energy. We did not find the hypothesized correlations of the slopes of psychological and physiological evening recovery trajectories with next-morning energy. These results suggest that although temporal characteristics of evening recovery processes are significant predictors of next-morning capacity to perform (Engle et al., 1995; J. F. Thayer et al., 2009), they do not significantly affect next-morning willingness to perform (Zijlstra et al., 2014). Furthermore, these results are consistent with prior research, which reported significant effects of evening recovery experience trajectories on energy later the next day, but not immediately the next morning (Maike Arnold et al., 2023). On the one hand, due to their temporal proximity, immediate bedtime recovery states (Parker et al., 2020) or nighttime recovery (Clinton et al., 2017) may affect morning energy stronger than temporal evening recovery characteristics. On the other hand, similar to cognitive performance effects, energy-promoting effects of evening recovery processes may rather be detectable later during the day when employees face new job stressors (Maike Arnold et al., 2023) or may rather predict fluctuating energy levels throughout the workday indicating stressor resilience rather than static morning energy (Wiegelmann et al., 2023). From the perspective of the ERM (Meijman & Mulder, 1998), which distinguishes between physical and mental load, it is also possible that energy is more susceptible to sustained physical load or insufficient physical recovery whereas cognitive functioning is more sensitive to cognitive load effects. Our sample that predominantly engaged in office work might therefore explain the absence of significant effects on next-morning energy.

Methodologically, our multi-method findings show that recovery effects extend beyond employees' subjective perceptions to measurable physiological and performance-related outcomes (Sonnentag et al., 2017), mitigating common method variance (P. M. Podsakoff et al., 2024). Furthermore, demonstrating the hypothesized effects of subjective and physiological recovery trajectories on next-morning cognitive functioning validates the sensitivity and feasibility of the short, smartphone-based SART as a recovery outcome measure (Perzl et al., 2024). Overall, the distinct associations of temporal characteristics of psychological and physiological evening recovery trajectories with next-morning recovery outcomes despite their similar U-shaped forms underscore the importance of a multi-modal operationalization of recovery from job stress and specific assumptions regarding 'sufficient' recovery (e.g., immediate or complete recovery).

Limitations and Future Directions

Although the fine-grained hourly assessments of evening recovery can be considered a strength enabling detailed tracking of short-term recovery effects (Ganster & Rosen, 2013; Sonnentag et al., 2017), the study's protocol may have been perceived as demanding and thus may have attracted a selective, rather low-stress sample. Chronically stressed individuals or those facing extreme job or personal demands may not have had the capacity to participate, and their recovery processes—potentially characterized by pathophysiological allostatic states (e.g., delayed or absent recovery; McEwen, 1998, 2003)—may differ significantly from those observed in our study. Moreover, the hourly evening assessments might have constrained or influenced participant's typical recovery behaviors. Future research could benefit from using evening reconstruction methods as an alternative (Maike Arnold et al., 2023; Kahneman et al., 2004).

The fact that our sample was a WEIRD convenience sample facing mainly mental load and working Monday to Friday during regular business hours with geographical proximity to the two participating German universities further limits the generalizability of our findings. However, trajectories of after-work recovery may look different for employees with different working hours facing mainly physical loads (e.g., industrial shift workers; Sloan et al., 2025). For the sake of generalizability, future studies should aim to replicate our study with a more diverse employee sample, particularly including shift workers.

Even though objective assessments can be seen as a valuable complement to questionnaire data (Sonnentag et al., 2017), both physiological and cognitive field measurements should be interpreted with caution (Laborde et al., 2017). Cognitive test procedures conducted in field studies—although validated for use in ambulatory settings (Perzl et al., 2024)—remain less standardized than those conducted in controlled laboratory environments. In a similar vein, physiological measurements in real-life settings are susceptible to artifacts, such as coughing, improper attachment of chest belts, or excessive movement which can never be fully controlled (Laborde et al., 2017). These issues challenge researchers to find a good balance between consequent data exclusion and non-excessive sample size reduction. Although both SART outcomes assess cognitive inhibition (Johnson et al., 2007; Manly et al., 2003), response style variability appears more sensitive to subjective and physiological recovery than inhibition errors. Future research could expand the present findings, for example, by examining how specific cognitive impairments translate to work behavior such as working fast but inaccurately vs. working carefully at a slower pace.

This study highlights the additional predictive value of recovery trajectories' slopes beyond psychophysiological states at the end of the workday (intercepts), offering insights into optimal temporal patterns of evening recovery processes. However, based on our study design, we can only draw conclusions regarding the consequences of effective evening recovery trajectories. In contrast, as we did not consider employees' evening activities and experiences, we cannot draw definitive conclusions about what might promote an effective recovery process after work. To derive actionable recommendations, future research should investigate the role of recovery activities and experiences for subjective and physiological evening recovery trajectories, taking into account potentially critical temporal dynamics, such as the need for immediate high psychological detachment after work (Maike Arnold et al., 2023; R. S. Grant et al., 2026).

Practical Implications

Our findings have several practical implications. Our results suggest that a more complete psychological recovery before bedtime fatigue and a more immediate and fast physiological recovery after work are particularly critical for ensuring next-day capacity to perform. In particular, our results indicate that next-morning impairments in employees' cognitive functioning may initially manifest in increased compensatory cognitive effort to meet task demands and performance standards instead of provoking immediate cognitive performance decrements (Bellgrove et al., 2004). Employers should be aware that even though immediate consequences of insufficient recovery may not be obvious, they pose intense load on employees (Meijman & Mulder, 1998). These load effects can accumulate if recovery remains 'insufficient' and eventually result in severe health problems (Meijman & Mulder, 1998). To counteract, employers could invest in preventive measures long before performance decrements surface.

To facilitate complete and immediate recovery after work, employers should ensure that employees' recovery processes can directly onset after work and are not interrupted during the evening. To help employees leave work behind mentally and avoid task-related rumination after work, employers can encourage end-of-day transition rituals, such as writing down tasks for the next day (Ashforth et al., 2000). Additionally, they can offer training programs to help employees psychologically detach from work during evenings (Karabinski et al., 2021). Furthermore, by reducing job stressors and promoting recovery during the day through regular work breaks (McEwen & Stellar, 1993; von Thiele et al., 2006), employers do not only prevent intense and sustained stress responses at work but also facilitate employees' psychological detachment after work (Sonnentag, 2018) to kick-start their evening recovery process (R. S. Grant et al., 2026). For the sake of employees' psychological detachment, relaxation, and control in the evening after work (R. S. Grant et al., 2026), supervisors should refrain from contacting employees during nonwork hours and clearly communicate that constant availability is not expected (Sonnentag et al., 2022). Also, adapting work schedules to employees' circadian rhythms may be an effective means to maximize after-work recovery time before the onset of circadian fatigue.

To maximize the extent of recovery before the natural, circadian rise in fatigue, employees should prioritize their preferred recovery activities earlier in the evening. Consciously relaxing during evening commute could be a feasible and effortless way to do so (Rivkin et al., 2025). Furthermore, modern technology, such as smartwatches, may help optimize the evening recovery process by recognizing negative deviations from the average physiological evening recovery process and proactively communicating these to users (Reeder & David, 2016). For example, when recovery is impeded (e.g., delayed or slow recovery), the smartwatch could proactively inform the user and propose recovery interventions (e.g., proposing a short meditation exercise; Feldman et al., 2023).

Conclusion

Overall, our findings underscore the value of a multi-method dynamic approach to assessing evening recovery, offering a more nuanced understanding of the evening recovery process and its effects on employees' next-morning recovery outcomes. Since a more complete early evening psychological recovery before the onset of circadian effects (fatigue) and a more immediate and faster physiological recovery (HRV) were positively linked to next-morning cognitive functioning, we recommend scheduling recovery activities as soon as possible after the end of work for optimal recovery effects.

CHAPTER V: GENERAL DISCUSSION

The three empirical studies building the core of this dissertation provide promising evidence for the feasible use of cognitive performance tests in occupational diary studies to measure momentary cognitive functioning at work. The main focus of Study 1 was to validate short smartphone-based versions of three cognitive performance tests (DSST, PVT, SART) measuring cognitive functioning domains sensitive to load effects and relevant for job performance. In Study 2 and Study 3, two adapted cognitive performance tests (DSST, SART) were exemplarily applied in occupational diary studies to evaluate their feasibility and utility for examining employees' momentary performance capacity in the context of fluctuating work demands and recovery.

Summary of Findings

The aims of Study 1 were to identify the shortest measurement durations of the DSST, PVT, and SART that allow for reliable and valid smartphone-based measurements of momentary cognitive functioning in diary studies and to test whether the adapted cognitive performance tests are sensitive to fluctuating work demands and recovery. Results of Study 1 show that the DSST provides reliable and valid indicators of cognitive functioning from a 90-second measurement duration onwards. Significant positive within-person associations were found for mental demands but not calmness with DSST performance. DSST efficiency improved significantly over measurement occasions, indicating practice effects. The PVT produced reliable and valid results from a 30-second measurement duration onwards. However, correlations of mental demands and calmness with PVT performance were not significant. Decreasing PVT performance over repeated measurement occasions points to motivational issues. The SART showed satisfying reliability of change from a 72-trial version onwards, which corresponds to an average measurement duration of about 90 seconds, but positive correlations of SART performance with self-reported concentration were only found between-person and not within-person. Both mental demands and calmness were positively associated with SART performance. Decreasing SART reaction time across measurement occasions suggests practice effects.

Due to promising findings on their reliability, validity, and sensitivity to work demands and recovery, I applied both the 90-second smartphone-based DSST and SART in workplace settings (Study 2, Study 3). In contrast, due to motivational issues and non-significant associations with work demands and recovery, I refrained from applying the adapted PVT repeatedly in a workplace setting. Declining participant motivation to complete the PVT may result from high participant burden (e.g., due to the test being perceived as very strenuous) and may lead to biased results and high drop-out rates.

The aim of Study 2 was to demonstrate the feasibility and utility of the 90-second DSST for occupational diary studies by investigating within-person associations of morning challenge and hindrance stressors with momentary cognitive functioning at three times during work (before the lunch break, after the lunch break, and at the end of work). No significant associations were found between hindrance stressors and DSST response efficiency. While morning challenge stressors were positively associated with DSST response efficiency before the lunch break, lagged associations of morning challenge stressors with DSST response efficiency in the afternoon (after the lunch break, at the end of work) were not significant.

Aiming to shed light on the role of recovery for work demands–cognitive functioning relations, I considered lunch break recovery (break duration, break detachment) as a moderator of lagged associations between morning work demands and afternoon cognitive functioning in Study 2. No significant within-person associations were found between lunch break recovery and DSST response efficiency. However, lunch break recovery significantly moderated the lagged associations between morning challenge but not hindrance stressors and DSST response efficiency in the afternoon, with either positive or negative effects depending on the quantity (duration) and quality (detachment) of lunch break recovery. On days with longer lunch breaks than usual, morning challenge stressors were positively associated with

DSST response efficiency after the lunch break and at the end of work. In contrast, these associations were negative on days with shorter lunch breaks. Similar effects were found for lunch break detachment, but only for DSST response efficiency at the end of work, not after the lunch break, and only for extreme values.

The aim of Study 3 was to demonstrate the feasibility and utility of the 90-second SART for occupational diary studies by testing the association of psychological (fatigue) and physiological (heart rate variability; HRV) evening recovery processes with cognitive functioning at the start of work the next morning. Evening recovery was indicated by significant U-shaped fatigue and HRV trajectories after the end of work. Effective evening recovery was positively associated with next-morning mental efficiency, in particular reduced mental effort (i.e., reduced SART response style variability but not commission errors), but not self-reported energy. Effective evening recovery was operationalized as U-shaped recovery trajectories with a later increase in fatigue (i.e., longer psychological recovery before the onset of circadian effects) and an earlier increase in HRV (i.e., more immediate and stronger physiological recovery after the end of work). No significant load effects were found between psychophysiological states at the end of work (i.e., fatigue and HRV trajectory intercepts) and SART performance the next morning when controlling for evening recovery.

Implications for the Use of Cognitive Performance Tests in Occupational Diary Studies

The three empirical studies provide insights into the shortest measurement durations of the smartphone-based cognitive performance tests providing reliable and valid measurements of momentary cognitive functioning in diary studies. Additionally, they inform about time trends across measurement occasions, indicating practice or motivational effects linked to repeated cognitive functioning assessments. Furthermore, empirical evidence of fluctuations in momentary cognitive functioning in the context of work demands and recovery leads to suggestions on appropriate cognitive functioning indicators, suitable research topics, and fruitful areas of application for each cognitive performance test. As a practical guide for researchers, Table 5.1 provides a summary of the empirical evidence and the derived suggestions for the application of the adapted cognitive performance tests in diary studies.

Implications for the 90-Second DSST

The findings of this dissertation suggest that the smartphone-based DSST can be applied with a 90-second measurement duration in occupational diary studies to reliably measure momentary cognitive functioning at work. I recommend DSST response efficiency as an indicator of cognitive functioning, that is, the ratio of the number of correct trials and mean reaction time. Considering primary and secondary performance indicators, this ratio includes information on achieved performance and related effort or performance costs (Hockey, 1997; Meijman & Mulder, 1998). Decrements in DSST response efficiency indicate mental fatigue (Meijman & Mulder, 1998). Being sensitive to decrements in both primary and secondary outcomes, DSST response efficiency can indicate load effects independently of employees' decision latitude and applied work procedure (i.e., regardless of whether employees reduce effort for the sake of well-being or maintain performance with compensatory effort). Applied in occupational diary studies, momentary DSST response efficiency can indicate if and at what costs employees can deal with work demands in this particular situation (Meijman & Mulder, 1998).

Table 5.1

Summary of Empirical Evidence on the Adapted Cognitive Performance Tests and Derived Suggestions for Their Application

	DSST	PVT	SART
Minimum measurement durations	90 seconds	30 seconds	72 trials (i.e., about 90 seconds)
Time trends over the study period	Increasing performance	Decreasing performance	Increasing performance for some secondary performance indicators
Cognitive functioning indicators	Response efficiency (i.e., the ratio of the number of correct trials and mean reaction time)	/	A combination of primary and secondary performance indicators (e.g., commission errors and response style variability)
Research topics	Cognitive resource mobilization and depletion (e.g., challenge stressor effects)	Circadian influences, sleep deprivation	Cognitive resource mobilization, depletion, and restoration (e.g., challenge stressor effects, recovery effects)
Areas of application	Mentally demanding settings (e.g., work, education, mastery experiences)	Shift work	Work and nonwork settings (e.g., work, education, leisure time)

Note. DSST = Digit Symbol Substitution Task. PVT = Psychomotor Vigilance Task. SART = Sustained Attention to Response Task. Since the cognitive performance tests were administered at different times and in different contexts, this information does not imply a direct comparison.

Opposing associations of morning challenge stressors with afternoon cognitive functioning as a function of lunch break recovery (Study 2) suggest that DSST response efficiency can be used as an indicator of resource pools (Meijman & Mulder, 1998). However, to detect fluctuations in resources, the DSST should be applied thoughtfully. First, the DSST seems to only detect fluctuations in cognitive resources. Due to its sensitivity to challenge stressor (Study 1, Study 2) but not hindrance stressor effects (Study 2), DSST response efficiency may be particularly sensitive to stimulating and load effects of work demands that highly depend on cognitive resources (e.g., difficult tasks; Young & Stanton, 2002). Second, when aiming to examine recovery effects, researchers should select the DSST only when the goal is to measure mobilized and accessible cognitive resource pools (e.g., recovery as a moderator of the relationship between work demands and momentary cognitive functioning during a sustained work period), rather than the sole restoration of resources (e.g., recovery as a predictor of momentary cognitive functioning at the end of the recovery period). Despite detecting recovery effects moderating the associations between challenge stressors and cognitive functioning (Study 2), direct associations of calmness (Study 1) and lunch break recovery (Study 2) with DSST efficiency were not significant.

That recovery effects are only significant when examined in the interplay with work demands indicates that the DSST captures the momentary pool of cognitive resources that is actually mobilized and accessible to dealing with upcoming demands instead of the whole replenished pool of resources that can be potentially mobilized (Meijman & Mulder, 1998; Young & Stanton, 2002). These results support construct validity, as the DSST measures working memory, which is defined as the momentary cognitive resources indeed available to information processing (D. C. Park, 2000). Furthermore, these results underscore the compatibility of the DSST with the definition of cognitive functioning as momentary performance capacity in the ERM (Meijman & Mulder, 1998). Overall, the findings of this dissertation indicate that DSST response efficiency may be effectively applied as an indicator of cognitive resource pools accessible to information processing (D. C. Park, 2000), for example, in occupational diary studies focusing on resource mobilization and depletion linked to work demands requiring cognitive resources. Beyond occupational settings, the DSST may be used to measure cognitive functioning in other mentally demanding contexts, such as educational settings at school or nonwork situations characterized by mastery experiences (e.g., playing chess; Cegolon & Jenkins, 2022; Könen et al., 2015).

Consistent findings in a sample of students (Study 1) and a sample of knowledge workers (Study 2), as well as for designs with one (Study 1) and multiple measurements per day (Study 2), highlight the feasibility of the short smartphone-based DSST for diary studies with occupational samples and different study designs. DSST response efficiency may be a particularly useful objective behavioral indicator of employees' performance capacity in white-collar work that typically lacks observable momentary performance indicators. Significant time trends across measurement occasions (Study 1, Study 2) indicate that researchers should consider practice effects when presenting the DSST repeatedly. In addition to presenting random combinations of digits and symbols in each measurement occasion, practice effects should be statistically controlled for.

Implications for the 30-Second PVT

Based on the findings of this dissertation, I recommend the use of the 30-second smartphone-based PVT in occupational diary studies only for very selected research questions for two main reasons. First, decreasing PVT performance over measurement occasions suggests that repeated PVT assessments are most likely linked to high participant burden. Second, not finding significant correlations of mental demands and calmness with PVT performance in Study 1 raises doubts regarding either the sensitivity of the test to fluctuations in work demands and recovery or the relevance of work demands and recovery for sustained attention. However, previous research indicates that short versions of the PVT may be sensitive and relevant to sleep deprivation (Gartenberg & Parasuraman, 2010) and subjectively perceived mental fatigue (Price et al., 2017). Hence, due to providing reliable and valid results (Study 1), the 30-second smartphone-based PVT may still represent a cost-efficient alternative to original longer versions of the PVT for research fields that largely rely on PVT assessments (e.g., research on circadian influences or shift work; Schmidt et al., 2007).

Implications for the 90-Second SART

The findings of this dissertation suggest that the smartphone-based SART can be applied in a 72-trial version (which corresponds to a measurement duration of about 90 seconds) in occupational diary studies. To detect mental load, primary performance indicators should be complemented with secondary performance indicators or indicators of effort invested in task completion (Hockey, 1997; Meijman & Mulder, 1998). Therefore, I recommend pairing the number of commission errors (commonly used as a primary performance indicator in the SART) with either mean reaction time or omission errors as secondary performance indicators or with response style variability indicating mental effort (Bellgrove et al., 2004). The results of Study 3 support the assumption that load effects may more immediately become apparent in increased compensatory effort (i.e., increased response style variability) than in reduced primary performance indicators (i.e., increased number of commission errors; Hockey, 1997; Meijman & Mulder, 1998; Sonnentag & Geurts, 2009). Hence, combining the number of commission errors with secondary performance indicators (e.g., mean reaction time, response style variability) allows for a comprehensive evaluation of mental fatigue with the SART.

Due to significant associations of momentary calmness (Study 1) and psychological and physiological evening recovery trajectories (Study 3) with SART performance, I recommend the SART for the evaluation of short-term load and recovery effects. This recommendation is further supported by two intervention studies that applied the adapted SART and found significant associations between relaxation and mindfulness meditation exercises during lunch breaks and subsequent performance in the adapted SART (Riedl et al., 2023; Riedl et al., 2024). Significant associations of psychological and physiological evening recovery trajectories with next-morning SART performance (Study 3) support the task's sensitivity to multimodal subjective and objective recovery effects. Replicating laboratory findings on the association between HRV and cognitive functioning (Forte et al., 2019; Nicolini et al., 2024), these findings support the validity of the adapted SART.

Significant positive associations between mental demands and SART performance in Study 1 suggest that the SART is not only sensitive to resource depletion and restoration but also to resource mobilization. Hence, the SART appears to indicate resource availability more globally but less specifically than the DSST. Therefore, potential fields of application for the SART are more versatile, covering work and nonwork settings (e.g., evening after work, weekend). For example, the adapted SART may allow environmental psychology researchers—typically applying cognitive performance tests in experimental laboratory studies and intervention studies with longitudinal designs (Bratman et al., 2012)—to objectively capture momentary cognitive functioning in real-life work and nonwork environments. Furthermore, the SART may be a useful tool providing objective behavioral indicators of white-collar workers' momentary performance capacity, as it provides insights into executive functioning (Irwin et al., 2020; Manly et al., 2002; Schmidt et al., 2007), which is particularly relevant for job performance in white-collar jobs (requiring planning, decision-making, etc.).

Findings on the association between recovery and cognitive functioning covering momentary correlations with subjective calmness (Study 1), recovery effects shortly after lunch break interventions (Riedl et al., 2023; Riedl et al., 2024), and delayed recovery effects over night with a time lag of several hours including sleep (Study 3) suggest that the SART may provide feasible and sensitive load and recovery indicators in diary studies with different study designs. The corresponding associations between recovery and SART performance in student (Study 1) and occupational samples (Study 3) support the feasibility of the cognitive performance test for occupational diary studies. The lack of within-person correlations between self-reported concentration and SART performance (Study 1) may not necessarily question the test's validity. Instead, the SART may be particularly useful in capturing unconscious, fast, and automatic cognitive functioning, which cannot be captured with self-reports (Meijman & Mulder, 1998). Finding significant recovery effects for cognitive functioning but not self-reported energy (Study 3) may underscore the test's high sensitivity to load effects, detecting changes immediately before they are consciously perceived (Sonnentag & Geurts, 2009). Significant time trends of SART reaction time across measurement occasions (Study 1) indicate that practice effects may be of relevance for some indicators and should be checked and statistically controlled for when applying the SART repeatedly.

General Remarks on Cognitive Functioning Assessments in Occupational Diary Studies

Generally, when presenting cognitive performance tests outside the laboratory in real-life settings, researchers should be aware that assessment situations are not standardized and measurements can be biased for different reasons (e.g., technical problems, distractions during task completion). Clear participant instructions (i.e., to conduct the test at a quiet place with a low risk of distraction) can be very useful to reduce the risk of biased assessments. Although assessments in the work context may in some professions take place in relatively standardized settings (e.g., offices), researchers are advised to collect information on the assessment situation with additional control variables. Capturing, for example, technical problems, distractions, or participant motivation allows researchers to control for potential bias after the end of data collection instead of controlling the actual assessment situations. For example, excluding measurements linked to technical problems or controlling for participants' motivation ensures valid results despite unstandardized assessment situations.

Furthermore, measurement time points should be chosen wisely, as the completion of cognitive performance tests requires mental effort and interrupts natural behavior. Due to their short measurement durations, all three cognitive performance tests are feasible tools for the combined assessment with self-report questionnaires in occupational diary studies with multiple daily assessments and assessment periods longer than one week (Hektner et al., 2007). However, if presented at the wrong time, the cognitive performance tests might interfere with the effects researchers aim to measure. For example, presenting cognitive performance tests repeatedly to employees during recovery periods may interrupt the restoration of cognitive resources, which the tests intend to measure. Also, assessments of cognitive functioning during work episodes may interrupt social interactions and focus on work tasks and may even present a hazard risk, for example, for employees handling machines. Therefore, optimally, researchers should present cognitive performance tests at the end of work or recovery periods to capture load or recovery effects. Generally, if researchers aim to collect cognitive performance data simultaneously with self-reports or physiological indicators, cognitive performance tests should be presented after the self-report questionnaire, and the physiological data should be extracted before the cognitive functioning assessment to avoid biased assessments. If aiming to measure cognitive functioning processes over time within work or recovery periods, the time interval between consecutive assessments should be maximized, and the measurement time points should be foreseeable or even self-initiated to minimize the impact of cognitive performance assessments on employees' natural behavior and to reduce participant burden. Event-based sampling (e.g., asking participants to complete a cognitive performance test before starting a new work task or recovery activity; Trull & Ebner-Priemer, 2013) may be a feasible approach.

Overall, this dissertation's objective findings on load and recovery effects support the robustness of previous research on the effects of work demands and recovery. Despite common method bias artificially inflating effect sizes in pure self-report studies (P. M.

Podsakoff et al., 2024), this dissertation's findings on the associations of challenge stressors and recovery with cognitive functioning are largely in line with previous research focusing on self-reported performance outcomes (Pindek et al., 2024; ten Brummelhuis & Bakker, 2012). This validating information is particularly valuable for studies that can solely utilize self-report questionnaires.

This dissertation also demonstrates the added value of cognitive performance tests beyond the scope of self-report questionnaires. Due to their high feasibility for occupational diary studies, the adapted DSST and SART can serve as a useful supplement or a genuine alternative to self-report questionnaires. Combining self-reports with cognitive performance tests contributes to existing research by capturing substantive outcomes underlying employee perceptions that may be unconscious, hence cannot be captured by self-reports (Meijman & Mulder, 1998; Sonnentag et al., 2017). Furthermore, combining typical psychological indicators with behavioral cognitive functioning contributes to a multidimensional understanding of load and recovery effects (Sonnentag & Geurts, 2009). Cognitive functioning—being a critical component of employees' work potential—may serve as a more proximate and sensitive alternative recovery outcome to subjective job performance (Meijman & Mulder, 1998; Sonnentag & Geurts, 2009) that may facilitate effective workplace interventions, particularly for professions that cannot objectively quantify job performance on a moment-to-moment level (e.g., knowledge work). Due to its general nature, cognitive functioning can be assessed independent of concrete job profiles, enhancing the comparability of studies on employee work potential across professions and research fields. These added values should encourage researchers to include the cost-efficient DSST or SART in their occupational diary studies.

Implications for Theory

Within this dissertation, I not only adapted and validated cognitive performance tests but also applied cognitive performance tests in workplace settings. The application of the adapted DSST and SART in occupational diary studies (Study 2, Study 3) provides insights into momentary cognitive functioning at work that allow for the derivation of theoretical implications linked to work demands, recovery, and their respective interplay.

Work Demands and Cognitive Functioning at Work

Focusing on the intensity and type of work demands as well as on the sustained exposure to work demands, the examined associations between work demands and cognitive functioning at work theoretically contribute to the ERM (Meijman & Mulder, 1998) and the CHSF (M. A. LePine, 2022). First, in line with the demand-induced strain compensation model of job stress (DISC; De Jonge & Dormann, 2003), the findings of this dissertation suggest that cognitive resource mechanisms are not equally relevant for all types of work demands. The positive association between morning challenge stressors and cognitive functioning before the lunch break (Study 2) supports the assumed cognitive resource mobilization following mentally demanding work demands postulated by the ERM (Meijman & Mulder, 1998), the CHSF (M. A. LePine, 2022), and cognitive resource theories (e.g., Young & Stanton, 2002). However, non-significant associations between hindrance stressors and cognitive functioning throughout the workday (Study 2) do not support the assumption that hindrance stressors deplete cognitive resources.

The non-significant associations between hindrance stressors and cognitive functioning do not contradict the assumptions of the ERM (Meijman & Mulder, 1998). Hindrance stressors may not constitute appropriate work demands for testing assumptions of the ERM (Meijman & Mulder, 1998), which primarily concern mental and physical load and underlying energy and cognitive functioning. Most hindrance stressors (e.g., conflicts, lack of information) may not be associated with a change in mental or physical load. Instead, negative associations between hindrance stressors and job performance may be explained by less time on task, for example, caused by interruptions or waiting time linked to missing information. Supporting this assumption, a recent meta-analysis found a direct negative association between hindrance stressors and job performance and showed stronger negative associations of hindrance stressors with task performance than with OCB (Pindek et al., 2024). Therefore, researchers should only argue based on the ERM (Meijman & Mulder, 1998) when the work demands in question are linked to physical or mental load.

Furthermore, the non-significant associations between hindrance stressors and cognitive functioning do not contradict the CHSF (M. A. LePine, 2022). Similar to the ERM (Meijman & Mulder, 1998), the CHSF (M. A. LePine, 2022) postulates that work demands are linked to engagement or disengagement (i.e., fluctuations in energy), mobilizing and/or depleting resources. However, in contrast to the ERM (Meijman & Mulder, 1998), underlying resource mechanisms in the CHSF (M. A. LePine, 2022) are not restricted to cognitive and energy resources. Hindrance stressor–performance relationships may still have an underlying mechanism of resource depletion, as the aforementioned meta-analysis found an indirect association between hindrance stressors and job performance via strain (Pindek et al., 2024). But, in contrast to challenge stressors, hindrance stressors may not primarily depend on cognitive resources. The matching principle suggests that associations between work demands, resources, and outcomes are stronger when all variables fit into the same domains (e.g., cognitive, emotional; Ji et al., 2024). Hence, while challenge stressors (e.g., time pressure, task difficulty) may be closely linked to cognitive resources, hindrance stressors (e.g., conflicts) may be primarily related to emotional resources. For example, empirical findings indicate that cognitive functioning may be highly affected by the intensity of mental work demands but less so by the intensity of emotional or physical work demands (Ji et al., 2024). This is in line with the CHSF (M. A. LePine, 2022), postulating that hindrance stressors are often accompanied by negative affect (e.g., anger, frustration) that may most closely relate to emotional resource depletion. Hence, the CHSF (M. A. LePine, 2022) and the matching principle (Ji et al., 2024) suggest that hindrance stressor effects may rather appear in fluctuations of emotional resources than cognitive resources.

Prospectively, it could be useful to extend the ERM (Meijman & Mulder, 1998) beyond physical and mental load, for example, by widening the focus to emotional load (e.g., characterized by frustration) as proposed in the DISC (de Jonge & Dormann, 2003). As postulated by the DISC (de Jonge & Dormann, 2003), the ERM (Meijman & Mulder, 1998) could cluster work demands in groups primarily affected by physical, cognitive, or emotional resources in accordance with the matching principle (Ji et al., 2024). The precise assumptions of the ERM (Meijman & Mulder, 1998) on underlying resource mechanisms (energy, cognitive functioning), in turn, could then be expanded to emotional resources. Conversely, the broad perspective of "the 'black box' of resource dynamics" (M. A. LePine, 2022, p. 245) in the CHSF could be reduced to energy, cognitive, and emotional resources. Adapting the two theoretical frameworks guided by the assumptions of the DISC (de Jonge & Dormann, 2003) would allow for both broader (ERM; Meijman & Mulder, 1998) and more specific insights (CHSF; M. A. LePine, 2022) into fluctuations in work demands, resources, and their consequences for job performance, health, and well-being. A better understanding of the associations between work demands and resources may help ensure employee well-being and functioning at work by enabling the provision of the specific resources that are needed (de Jonge & Dormann, 2003; Ji et al., 2024).

Second, by examining the associations of morning challenge stressors with cognitive functioning at three times at work (before the lunch break, after the lunch break, and at the end of work), considering the moderating role of lunch break recovery for afternoon cognitive functioning (Study 2), this dissertation provides information on the conditional persistence of resource mobilizing effects throughout a period of sustained exposure to work demands. Supporting the episodic nature of the ERM (Meijman & Mulder, 1998) and the CHSF (M. A. LePine, 2022), positive associations between challenge stressors and cognitive functioning do not only appear concurrently but can indeed persist until the end of the workday. In line with the assumptions of the ERM (Meijman & Mulder, 1998) on the sustained exposure to work demands, if resource restoration is neglected, the initial resource-mobilizing effects of morning challenge stressors can shift into depleting effects further into the workday (e.g., at the end of work). Empirical evidence on the opposing associations between morning challenge stressors and afternoon cognitive functioning depending on resource restoration during the lunch break (Study 2) illustrates the critical interplay between mobilization, resource restoration, and resource depletion at work, providing concrete first insights into the role of cognitive resources in the so-called "'black box' of resource dynamics" (M. A. LePine, 2022, p. 245) of the CHSF.

Recovery and Cognitive Functioning at Work

Further theoretical contributions can be derived from the associations between recovery and cognitive functioning. This dissertation empirically supports the definition of recovery as a process of psychophysiological unwinding that restores strained resources (Geurts & Sonnentag, 2006; Sonnentag & Geurts, 2009). First, finding the assumed U-shaped psychological and physiological recovery trajectories in the evening after work (Study 3) empirically supports the definition of recovery as a psychophysiological process (Geurts & Sonnentag, 2006; Meijman & Mulder, 1998; Zijlstra et al., 2014). By applying this dynamic approach, this dissertation enhances the theoretical understanding of how recovery unfolds in the evening after work. Second, cognitive performance tests detecting significant relationships between recovery and cognitive functioning directly (Study 3) and via moderation effects (Study 2) support the postulated cognitive resource restoration during recovery periods (Sonnentag & Geurts, 2009). Cognitive functioning being a proximate, sensitive, and substantive recovery outcome, these findings suggest that the restoration of cognitive resources may be a critical underlying mechanism of recovery effects perceived in more distant outcomes (e.g., positive affect, job performance; Sonnentag & Geurts, 2009; Sonnentag et al., 2017).

Additionally, this dissertation contributes to a multimodal understanding of recovery and sheds light on psychological and physiological recovery processes underlying behavioral recovery outcomes (i.e., cognitive functioning) at work (Sonnentag & Geurts, 2009). In particular, this dissertation provides insights into physiological recovery trajectories based on employees' momentary HRV (Study 3), objective indicators that are often neglected in recovery research (Steed et al., 2021). Thereby, this dissertation enhances our understanding of physiological allostatic adaptation in the evening after work and its consequences for next-morning cognitive functioning, providing empirical evidence for assumptions of the allostatic load model (McEwen, 1998). The combined assessment of HRV and cognitive functioning in an occupational diary setting further enriches previous cross-sectional and longitudinal studies often conducted in standardized settings with real-world data (Forte et al., 2019; Nicolini et al., 2024). Significant associations of temporal evening recovery characteristics, captured by psychological and physiological recovery trajectories, and next-morning cognitive functioning provide insights into the complex interplay of psychological, physiological, and behavioral recovery indicators (Sonnentag & Geurts, 2009).

Furthermore, the findings of this dissertation enhance our understanding of the critical importance of recovery during lunch breaks and evenings after work to ensure cognitive functioning from the beginning to the end of the workday and to avoid accumulating load effects (Meijman & Mulder, 1998). On the one hand, findings of Study 2 underscore the critical role of lunch break recovery to manage resources and to avoid compensatory effort further into the workday, maintaining employees' work potential despite sustained exposure to work demands (Meijman & Mulder, 1998; Zijlstra et al., 2014). On the other hand, the findings of Study 3 highlight the critical role of evening recovery to restore strained psychophysiological states after work and to avoid compensatory effort the next morning, resetting employees' work potential for the next workday (Meijman & Mulder, 1998). Hence, the empirical findings of this dissertation indicate that, due to restoring cognitive resources

(Sonnentag & Geurts, 2009), recovery between consecutive work periods can counteract resource depletion at work as assumed by the CHSF (M. A. LePine, 2022) and interrupt accumulating load effects by avoiding compensatory effort as postulated by the ERM (Meijman & Mulder, 1998).

By providing empirical evidence on lunch break recovery significantly moderating the association between morning challenge stressors and afternoon cognitive functioning at work (Study 2), this dissertation highlights the importance of considering recovery not only as a predictor but also as a moderator, as postulated by key theoretical frameworks (Meijman & Mulder, 1998; Sonnentag & Fritz, 2015). The findings of this dissertation indicate that recovery can mitigate load effects during periods of sustained exposure to work demands (e.g., throughout the workday), identifying lunch break recovery as a critical boundary condition of resource mobilizing effects at work (e.g., linked to challenge stressors). Thereby, this dissertation adds empirical evidence to the small body of research investigating recovery as a moderator of the relationship between work demands and work outcomes (e.g., Sonnentag et al., 2010).

Also, the empirical results of this dissertation highlight the relevance of quantitative recovery (i.e., the duration of the recovery period) for cognitive resource restoration. The results of Study 3 suggest that the evening recovery period should be maximized (by a later increase in circadian fatigue and an earlier increase in HRV) to avoid impairments in cognitive functioning the next morning at work due to residual load effects. This enriches prior recovery research, particularly occupational diary studies, primarily examining qualitative aspects of recovery activities, experiences, and environments (Sonnentag et al., 2017). Furthermore, in line with the ERM (Meijman & Mulder, 1998), the results of Study 2 suggest that on days with higher morning challenge stressors, longer lunch breaks than usual are necessary to prolong stimulating and to avoid depleting effects. By focusing on lunch break duration as a moderator of the relationship between work demands and cognitive functioning, this dissertation enriches prior research investigating the role of quantitative recovery aspects, such as the break duration, for resource restoration (e.g., E. M. Hunter & Wu, 2016). Prior research typically focused on break duration as a predictor (Lyubykh et al., 2022), often neglecting that the time needed for recovery highly depends on the preceding exposure to work demands (Sonnentag & Zijlstra, 2006). Overall, the results of this dissertation highlight the relevance of quantitative recovery for cognitive resource restoration, which is a critical underlying component of employees' work potential (Meijman & Mulder, 1998).

The Interplay of Work Demands and Recovery

Overall, the findings of this dissertation highlight the necessity to consider the complex interplay between work demands and recovery, as postulated by the ERM (Meijman & Mulder, 1998), even when investigating only the associations of either work demands or recovery with psychological, physiological, or behavioral outcomes. The results of Study 2 underscore that if the respective interplay of work demands and recovery is neglected, independent interpretations of work demands or recovery effects may result in biased conclusions. For example, if the non-significant direct associations between morning challenge stressors and afternoon cognitive functioning were interpreted without considering recovery as a moderator, the significant opposing effects of challenge stressors on afternoon cognitive functioning depending on the lunch break duration would have remained masked. Similar to prior research (Pindek et al., 2024), this could have led to the conclusion that challenge stressors are only concurrently linked to cognitive functioning, although stimulating effects can last under the condition of adequate recovery.

Implications for Practice

Overall, this dissertation supports the notion that cognitive functioning fluctuates at work (Study 2, Study 3). As cognitive functioning indicates employees' performance capacity and is a critical component of their work potential (Meijman & Mulder, 1998), it should be one of the primary goals of employers to maintain or even promote cognitive functioning at work. Based on empirical findings, this dissertation offers suggestions to employees and employers on how to maintain and enhance employee cognitive functioning at work and how to avoid cognitive functioning decrements. In line with the ERM (Meijman & Mulder, 1998) and the CHSF (M. A. LePine, 2022), I focus on work demands and recovery as the primary levers to manage employee cognitive functioning, aiming to reduce the costs linked to job performance for the ultimate sake of employee health and well-being (Hockey, 1997; Meijman & Mulder, 1998).

Managing the Appraisal of Work Demands

The findings of this dissertation (Study 1, Study 2) indicate that, in contrast to hindrance stressors, challenge stressors are (under some circumstances) positively associated with cognitive functioning, particularly with high mental efficiency. High mental efficiency indicates that employees can deal with upcoming work tasks more effortlessly, having the cognitive capacity to work more accurately without slowing down or faster without making more mistakes (Hockey, 1997; Meijman & Mulder, 1998). In contrast, low mental efficiency is often linked to compensatory effort—which can have serious consequences for employee well-being—or performance decrements (Hockey, 1997; Meijman & Mulder, 1998).

Hence, it could be helpful to facilitate challenge appraisals and reduce hindrance appraisals of work demands, particularly those inherent to the job profile. Employers could offer stress appraisal trainings (Jamieson et al., 2018) or reduce unnecessary tasks (Kronenwett & Rigotti, 2019) to encourage employees to interpret work demands as manageable and linked to potential resource gain. However, the findings of this dissertation (Study 2) indicate that the beneficial effects of challenge stressors on cognitive functioning may last only for a short period of time and—due to mental fatigue resulting from sustained exposure to work demands (M. A. LePine, 2022; Meijman & Mulder, 1998)—may even shift in the opposite direction a few minutes or hours later on the same workday. Therefore, employers should not thoughtlessly increase challenge demands aiming to promote job performance.

Prioritizing Recovery

Instead, employers should make sure to prioritize recovery at work to maintain and even promote employee cognitive functioning throughout the workday. The results of this dissertation indicate that lunch break duration plays a critical role in maintaining positive associations between challenge stressors and employee cognitive functioning throughout the workday and in avoiding negative associations of morning challenge stressors with cognitive functioning in the afternoon (Study 2). To effectively manage employees' cognitive functioning, employers should make sure that employees do not shorten their lunch breaks on challenging, mentally demanding days. Instead, to prolong the stimulating effects of challenge stressors and promote cognitive functioning, employers should encourage employees to take longer lunch breaks on those days. Leaders should act as role models, setting an example to employees by taking extended breaks, particularly on highly demanding workdays, instead of reducing breaks or skipping lunch on these days. Furthermore, employers should raise awareness and discourage self-endangering behavior associated with high work demands, such as working longer hours (Baethge et al., 2019). In addition, short mindfulness exercises may help to ensure recovery despite high work demands, counteracting the recovery paradox (Riedl et al., 2024; Sonnentag, 2018). Against the backdrop of prioritizing recovery, challenge stressors in the morning could indeed be a good start to an efficient workday, as they may sustainably promote cognitive functioning until the end of work.

However, employees can only have a good start to an efficient workday if they recovered well from the preceding one (Binnewies et al., 2009; Meijman & Mulder, 1998). Therefore, employers' responsibility for employee well-being should not end at the end of the workday. This dissertation demonstrates that evening recovery after work is another critical factor to ensure cognitive functioning at work, more specifically in the morning at the beginning of a new workday (Study 3). If employees start their workday with residual mental load, needing to invest compensatory effort to uphold performance standards, load effects may seriously accumulate throughout the day. In contrast, if employees start their workday with high cognitive functioning, they are well prepared to deal with upcoming work demands without overburdening themselves.

This dissertation suggests two tackling points to optimize evening recovery. First, the findings of this dissertation indicate that the early evening recovery period—before fatigue increases due to circadian influences (Hülsheger, 2016)—should be maximized. To maximize recovery before circadian influences dominate, employers should align shift schedules with employees' individual chronotypes or maximize employees' work time autonomy to allow them to work in synchrony with their circadian rhythms (Vetter et al., 2015). This would allow employees to finish work early enough to maximize the recovery period before experiencing bedtime fatigue. Second, the findings suggest that recovery should start immediately after the end of work. To support the shift from work life to private life, employers can actively support employees in applying boundary management strategies. For example, employers should refrain from contacting employees after work and instead encourage employees to activate an out-of-office message before leaving the office and not check work e-mails during nonwork time (Haun et al., 2022). Furthermore, to maximize recovery immediately after work, employees could proactively use their way home from work as a period dedicated to recovery. Just a small detour on the way home, walking through the park instead of along the main road, could boost recovery immediately after work (Pasanen et al., 2018; Schaupp et al., 2025). Alternatively, commuting times on the train could be actively used for recovery, for example, by listening to a relaxing podcast or doing meditation exercises (Rivkin et al., 2025).

With lunch break duration and the onset and duration of early after-work recovery being linked to beneficial effects, temporal aspects of recovery seem to play a critical role in maintaining and enhancing cognitive functioning at work. The critical role of recovery duration highlights the fundamental need to take adequate time for recovery at all (Study 2, Study 3) before elaborating on how employees should optimally spend this time (Riedl et al., 2024). Hence, employers and employees should both protect recovery periods against intruding additional work hours. Furthermore, the results of Study 3 indicate that the effectiveness of recovery activities, experiences, and interventions may depend on their timing. Therefore, practitioners should thoughtfully choose not only the content of recovery interventions but also their timing. The results of this dissertation suggest that evening recovery interventions may be most effective if scheduled at the beginning of the evening. However, more research is needed to support these first indications and to provide temporal advice on further recovery periods.

Overall, this dissertation underscores that work demands or recovery alone do not have (sustainable) positive effects on momentary cognitive functioning at work. In contrast, the thoughtful combination of high challenge stressors and adequate lunch break and evening recovery can have benefits for cognitive functioning from the beginning until the end of the workday. As load effects accumulate over time, lunch break and evening recovery do not only play a critical role in maintaining cognitive functioning across one or a few workdays but also over longer periods characterized by repeated exposure to work demands (e.g., across the workweek or across one work season until the next holiday; Meijman & Mulder, 1998).

Monitoring Cognitive Functioning

Cognitive performance tests may not only be useful to practice by providing empirical insights into fluctuations in momentary cognitive functioning at work but may also be of explicit practical utility by serving as tools of real-time monitoring of mental load (Sharma et al., 2023). Referring to explicit practical use cases of the DSST and SART, employers could consider reduced mental efficiency in these tests as early warning signs for mental fatigue that may only be observed in performance or well-being decrements with a certain delay

(Meijman & Mulder, 1998; Sonnentag & Geurts, 2009). As real-time monitoring systems are getting increasingly common, we are already used to our car or smartwatch telling us when to take a break. Similarly, repeated cognitive assessments at work could provide information on cognitive functioning deviations from person means as indicators of decreasing performance capacity and increasing need for recovery. This information could not only prevent long-term health consequences by avoiding compensatory effort (Meijman & Mulder, 1998) but also serious workplace accidents resulting from mental fatigue (Dorrian et al., 2007).

However, it must be noted that, compared to non-invasive systems, repeated 90-second cognitive performance tests are much more burdensome and may therefore only serve as feasible real-time monitoring systems in very specific use cases that justify the time and effort they require. Examples could be work situations that are associated with serious consequences for clients (e.g., heart surgeries) or the employees themselves (e.g., repairing under high-voltage current) in the case of errors. Alternatively, cognitive performance tests could serve as a secondary safety net following primary warning signals stemming from non-invasive systems. For example, if the steering wheel detected mental fatigue and asked a bus or truck driver to interrupt their trip, the driver could be asked to complete a cognitive performance test before continuing the journey to make sure they are again capable of driving. This procedure could reduce the risk of severe traffic accidents linked to mental fatigue (Dorrian et al., 2007).

In the future, artificial intelligence may allow detecting mental fatigue in other non-invasive ways, such as eye movements in front of a webcam, typing behavior, or changes in employees' intonation during a meeting. The DSST and the SART could then serve as helpful tools to validate those innovative methods in occupational settings. Furthermore, providing additional insights into the underlying physiological mechanisms of cognitive functioning at work, the adapted cognitive performance tests could validate non-invasive HRV measurement (e.g., through smartwatches) as a valid, non-invasive, and widely accepted tool to indicate mental fatigue at work (Forte et al., 2019; Nicolini et al., 2024; Sonnentag & Geurts, 2009).

Strengths and Limitations

This dissertation and the three included empirical studies come with several strengths and limitations. These refer to the theoretical conceptualization of the dissertation and the methodological implementation in the empirical studies.

Theoretical Conceptualization

The strengths and limitations linked to the theoretical conceptualization are based on the consideration of theoretical postulations of the ERM (Meijman & Mulder, 1998) and CHSF (M. A. LePine, 2022). In particular, the critical points refer to the model components captured by this dissertation and the scope of the examination of underlying resource dynamics.

Model Components of the ERM and the CHSF. The main theoretical strength of this dissertation is its focus on cognitive functioning, which is a core element of the ERM (Meijman & Mulder, 1998), sensitive to load and recovery effects, and meaningful for employee well-being and job performance across different professions (Nye et al., 2022; Young & Stanton, 2002). Due to its objective and proximate nature, cognitive functioning can provide sensitive, robust, and proximate insights into short-term load effects, allowing for effective interventions to avoid well-being and performance decrements at work (Sonnentag & Geurts, 2009; Sonnentag et al., 2017). While Study 2 focused solely on cognitive functioning, its combined assessment alongside energy can be considered a strength of Study 3, capturing both components of employee work potential. Significant results for cognitive functioning but not for energy underscore that changes in work potential may be detectable in sensitive unconscious measures of cognitive functioning, although not (yet) consciously perceived in energy fluctuations.

An additional strength of this dissertation is that, in line with its theoretical framework (ERM; Meijman & Mulder, 1998), cognitive functioning was operationalized as mental efficiency. Momentary mental efficiency indicates at what costs employees can deal with upcoming work demands in a particular situation (Hockey, 1997; Meijman & Mulder, 1998), one of the central questions the ERM aims to answer. This operationalization is of high practical value, as it can capture both performance decrements and additional compensatory effort (Hockey, 1997; Meijman & Mulder, 1998). By operationalizing mental efficiency once by the ratio of primary and secondary performance (Study 2) and once by the distinction between cognitive performance and cognitive effort (Study 3), this dissertation not only provides general insights into fluctuations in mental efficiency (Study 2) but also specific insights into their main driver (i.e., compensatory effort; Study 3).

Furthermore, it can be considered a strength that this dissertation not only focused on the intensity of work demands as a predictor of cognitive functioning but also distinguished challenge and hindrance stressors and took the sustained exposure to work demands across the workday into account (Study 2). Thereby, this dissertation considered theoretical characteristics of work demands postulated by the ERM (Meijman & Mulder, 1998) and differentiated by stressor type as proposed by the CHSF (M. A. LePine, 2022). Due to its comprehensive approach, this dissertation not only provides information on the association of high and low work demands with cognitive functioning at work but can also differentiate these associations by the type of work demands (i.e., challenge and hindrance stressors) and the duration of exposure to work demands, allowing for more detailed conclusions.

However, that this dissertation did not account for employees' decision latitude is a limitation. Decision latitude may be a critical moderator indicating whether load effects result in a decrease in primary performance outcomes or whether primary performance outcomes are maintained by sacrificing secondary performance standards or investing increased effort (Meijman & Mulder, 1998). This may be especially a limitation of Study 3, as the moderating effects of decision latitude are particularly relevant when performance and related effort are interpreted separately. In this case, employees' differing performance standards and work procedures may mask significant overall differences in mental efficiency. In contrast, this may not be an issue for Study 2, as the ratio of performance and related effort decreases no matter if primary or secondary performance decreases or effort increases, hence independently of employees' decision latitude.

It can be considered a strength that this dissertation explores recovery and its role for cognitive functioning at work from different angles and perspectives. By considering lunch break recovery (Study 2) and evening recovery (Study 3), this dissertation focuses on two critical recovery periods interrupting consecutive work periods, hence, potentially interrupting accumulating load (Meijman & Mulder, 1998). By covering recovery at work (Study 2) and after work (Study 3), this dissertation allows for comprehensive practical implications to promote employee recovery throughout the day. Approaching recovery from two definitions focusing either on ensuring employee functioning at work (Zijlstra et al., 2014) or easing employee strain after work (Geurts & Sonnentag, 2006; Sonnentag & Geurts, 2009), this dissertation sheds light on recovery as a moderator of the relationship between work demands and cognitive functioning at work (Study 2) and as a predictor of cognitive functioning at the start of the next workday (Study 3). Considering quantitative (lunch break duration) and qualitative aspects (lunch break detachment) of recovery (Study 2) and examining the recovery process with trajectories (Study 3) lives up to the theoretical assumptions of the ERM (Meijman & Mulder, 1998) and enriches previous recovery research focusing mainly on state measurements of recovery experiences (Sonnentag et al., 2017). Furthermore, including psychological (fatigue; Study 3), physiological (HRV; Study 3), and behavioral recovery indicators (cognitive functioning; Study 3) provides a multidimensional view on recovery, enriching previous recovery literature largely focusing on psychological recovery indicators (Sonnentag & Geurts, 2009; Steed et al., 2021). It should be noted, however, that this dissertation has a strong focus on temporal aspects of recovery (i.e., lunch break duration, evening recovery processes), largely neglecting qualitative recovery (e.g., recovery activities, experiences, and environments) with the exception of lunch break detachment.

Additionally, as the ERM (Meijman & Mulder, 1998) underscores the need to consider the environment, it is a limitation that environmental aspects were not explicitly taken into account in this dissertation. The recovery environment may be of critical relevance for the restoration of cognitive resources (Ohly et al., 2016). Also, the environment in which work demands need to be met may affect load effects by either posing additional demands on employees or providing resources (Demerouti et al., 2001). Additionally, differing environments during cognitive functioning assessments may reduce their comparability (Verhagen et al., 2019). However, at least for Study 2 and Study 3, it can be assumed that—due to the assessments taking place in comparable situations (every day at about the same time at work)—for most participants (e.g., office workers), the environment was largely consistent across the repeated cognitive functioning assessments.

Although the strong focus on work demands and recovery as critical predictors of cognitive functioning, as postulated by the ERM (Meijman & Mulder, 1998), can be considered a strength of this dissertation, it is a limitation that the association between momentary cognitive functioning and job performance was not examined. Despite empirical evidence of the association between cognitive functioning and job performance from cross-sectional (e.g., Nye et al., 2022) and longitudinal research (e.g., Lemonaki et al., 2021), little is known about the relationship between momentary cognitive functioning and different dimensions of job performance on a momentary or day level. Even though postulated by the ERM (Meijman & Mulder, 1998), it remains unclear if and to what extent deviations in momentary cognitive functioning at work translate into more distant work-related outcomes (e.g., job performance, employee well-being).

Underlying Resource Mechanisms of the ERM and the CHSF. It can be considered a strength that—by considering cognitive functioning as a substantive outcome underlying perceived well-being and performance (Lemonaki et al., 2021; Sonnentag et al., 2017)—this dissertation provides empirical insights into core underlying mechanisms of seminal conceptual frameworks (ERM; Meijman & Mulder, 1998; CHSF; M. A. LePine, 2022). Being a resource-dependent, potentially unconscious, and proximate load and recovery indicator (Ihle et al., 2015; M. A. LePine, 2022; Meijman & Mulder, 1998; D. C. Park, 2000; Sonnentag & Geurts, 2009; Young & Stanton, 2002), cognitive functioning is highly suited to test the postulated cognitive resource mechanisms underlying perceived load and recovery effects of the ERM and the CHSF. Considering the resource managing potential of lunch break recovery (Zijlstra et al., 2014), this dissertation provides empirical insights into cognitive resource gains and losses and their respective interplay at work as postulated by the ERM (Meijman & Mulder, 1998) and the CHSF (M. A. LePine, 2022) and identifies recovery as a critical tackling point to maintain and promote employees' work potential.

However, due to not testing cognitive functioning as a mediator, for example, of the association between work demands and job performance, this dissertation does not provide profound evidence that fluctuations in cognitive functioning are indeed an underlying mechanism in the ERM (Meijman & Mulder, 1998) and the CHSF (M. A. LePine, 2022). Additionally, the focus on cognitive functioning considers cognitive resources as only one aspect of "the 'black box' of resource dynamics" (M. A. LePine, 2022, p. 245) in the CHSF. Hence, future research investigating challenge and hindrance stressor effects should apply a comprehensive approach including cognitive functioning and further resources (e.g., emotional resources) and examining them as mediators of associations between work demands and work-related outcomes (e.g., job performance, employee well-being).

Methodological Implementation

Beyond the theoretical conceptualization, the methodological implementations in the three empirical studies included in this dissertation also have strengths and limitations. Critical points refer to the cognitive performance tests, the research designs, and the samples.

Cognitive Performance Tests. The careful selection and adaptation of the cognitive performance tests and their exemplary application in occupational diary studies can be considered the main methodological strength of this dissertation, ensuring valid and reliable measurements of momentary cognitive functioning in field contexts. Cognitive performance tests typically used in experimental laboratory research in the field of cognitive psychology were selected based on their relevance for load effects and job performance. To increase their feasibility for repeated assessments in diary studies, the cognitive performance tests were presented on smartphones and shortened to the minimum duration guaranteeing satisfying reliability of change. This evidence-based approach ensures their effective application in occupational diary studies.

The exemplary application of the adapted cognitive performance tests in occupational diary studies illustrates the tests' feasibility and utility for research on work demands and recovery effects and allows for suggestions of other fruitful application contexts. Offering a thorough evaluation of the eligibility of cognitive performance tests for the objective assessment of employees' momentary performance capacity in occupational diary studies, this dissertation paves the way for larger methodological variety in occupational health psychology and organizational behavior research largely dominated by subjective self-reports (Sonnentag et al., 2017; Steed et al., 2021). Combining subjective and objective measurements reduces the risk of common method bias, hence contributing to more robust research findings (P. M. Podsakoff et al., 2024).

However, it can be considered a limitation that this dissertation did not compare field assessments with the shortened smartphone-based cognitive performance tests to standardized laboratory assessments with the original versions of the tests to ensure their reliability. Hence, it remains unclear whether the adapted cognitive performance tests capture the same cognitive functioning domain as their original versions. Particularly for the PVT, it is questionable whether 30-second measurements can depict sustained attention, typically measured with much longer measurement durations (Schmidt et al., 2007). However, the comparability of field assessments and laboratory assessments may be generally limited, as repeated field assessments measure typical cognitive functioning in everyday situations, while one-time laboratory assessments measure maximum cognitive functioning under standardized conditions.

Even though the use of cognitive performance tests in occupational diary studies is considered a strength of this dissertation, this methodology also comes with some weaknesses. In contrast to laboratory assessments with standardized test conditions, ambulatory assessments in everyday life may be biased, for example, due to distractions (Bolger et al., 2003; C. D. Fisher & To, 2012; Sliwinski et al., 2018). Furthermore, cognitive functioning can be affected by third variables such as time-of-day effects linked to the circadian rhythm or participants' age (Daniëls et al., 2020; Manly et al., 2002; Schmidt et al., 2007; Verhagen et al., 2019; Weizenbaum et al., 2020). Therefore, the rare inclusion of control variables (e.g., practice effects in Study 1 and Study 2, technical problems and distractions in Study 3) can be considered a limitation of this dissertation. The lack of control variables may particularly have been a problem in Study 1, comprising three-minute measurement durations and semi-random assessment time points in very diverse real-life situations and times of day. In contrast, in Study 2 and Study 3, participants completed the tasks every day at about the same time at work (e.g., daily at the start of work), which should be linked to more standardized and comparable assessment conditions (e.g., similar time of day, similar environment). Furthermore, presenting cognitive performance tests with 90-second measurement durations in Study 2 and Study 3 should have reduced the risk of distractions and low participant motivation by keeping the cognitive performance tests as short as possible (Bolger et al., 2003; C. D. Fisher & To, 2012; Sliwinski et al., 2018). Future research should include at least a few key control variables to ensure a certain minimum reliability by excluding assessment situations potentially biased because of technical problems, distractions, or limited participant motivation.

Research Designs. The research designs of Study 2 and Study 3, accounting for time lags between most predictors and outcomes, can be considered a methodological strength of this dissertation. The temporal distance between associated variables does justice to the episodic nature of the ERM (Meijman & Mulder, 1998) and the CHSF (Cavanaugh et al., 2000; M. A. LePine, 2022), and—additionally to the multidimensional measurement approaches covering cognitive performance tests, physiological measurements, and self-report questionnaires—further reduces the risk of common method bias (P. M. Podsakoff et al., 2024). Applying cognitive performance tests at four different time points at work (before work, before and after the lunch break, and at the end of the workday) further supports the feasibility of cognitive functioning assessments at work. However, it can be considered a limitation that, despite its time-lagged designs, this dissertation does not allow for causal conclusions. Future research should opt for experimental designs (e.g., manipulating work demands or recovery) or cross-lagged panel models to allow for causal interpretations.

Samples. Limiting the interpretability and generalizability of the findings of this dissertation, all three empirical studies were conducted with relatively small WEIRD samples (i.e., western, educated, industrialized, rich, and democratic; Roberts et al., 2020). The sample sizes in this dissertation appear rather small compared to web-based diary studies (often focusing solely on self-reports) comprising on average 835 measurements of 83 participants (Gabriel et al., 2019). The smaller-than-average sample sizes—particularly at the person-level with 46–65 participants—can be justified with high data collection efforts linked to the cognitive performance tests (conducted with study smartphones) and physiological measurements (Study 3; Steed et al., 2021).

However, for several reasons, power issues should be a less serious concern of this dissertation. First, the focus of this dissertation lies on the within-person level, which is rarely underpowered (Gabriel et al., 2019). Cross-level effects—which require a certain minimum number of participants for adequate power—are not part of any of the included empirical studies (Gabriel et al., 2019). Second, although being smaller than average, the sample sizes in this dissertation are still comparable to diary studies with similar designs (e.g., Bissing-Olson et al., 2013; Norton et al., 2017). If expected effects exist, even smaller-than-average samples may be powerful enough to detect them (Gabriel et al., 2019). Limited interpretability due to the small sample sizes would therefore mainly apply to non-significant results. Third, Gabriel et al. (2019) argue that "overpowered" samples are a much larger concern than "underpowered" samples, as they may detect very small effects without any practical relevance. Hence, small sample sizes may even indicate a certain practical relevance of the detected significant effects.

Without a doubt, the WEIRD samples are a general limitation of this dissertation, particularly limiting the generalizability of its findings. However, given the underlying aims and contributions, to some extent, the very specific samples can also be considered a strength. On the one hand, limiting the regional radius for participant acquisition ensured high data quality, as providing cognitive performance tests on study smartphones with in-person instructions standardized technical preconditions (e.g., screen size, screen response delay) and reduced the risk of user errors during data collection. On the other hand, the focus on white-collar workers allowed for the evaluation of cognitive performance tests in occupational groups that hardly provide any observable momentary behavioral performance indicators (Hopp et al., 2009; Meijman & Mulder, 1998). Hence, the added value of cognitive functioning assessments indicating employees' performance capacity may be particularly high for these professional groups (P. M. Podsakoff et al., 2024). Nonetheless, future research should further evaluate the cognitive performance tests in other cultural and occupational settings to also provide substantial insights into fluctuations in cognitive functioning in underrepresented populations.

Avenues for Future Research

This dissertation implies several avenues for future research. Building upon this dissertation and the ERM (Meijman & Mulder, 1998), it could be particularly interesting to further explore how cognitive functioning translates into job performance and how recovery and environmental aspects affect cognitive functioning. Additionally, future research should test the cognitive performance tests in additional application contexts.

Cognitive Functioning in the ERM

Overall, according to the ERM (Meijman & Mulder, 1998), cognitive functioning can be considered a critical underlying factor of associations of work demands and recovery with job performance and well-being. Fluctuating work demands comprise task demands and environmental aspects (Meijman & Mulder, 1998).

Cognitive Functioning and Job Performance. Future research should provide closer insights into within-person associations of DSST and SART performance with different dimensions of job performance to further support the ecological validity and practical relevance of the cognitive performance tests. Similar to cross-sectional and longitudinal associations, at work, some cognitive functioning domains may be particularly relevant for specific performance outcomes (e.g., task performance, training performance, OCB; Lemonaki et al., 2021; Nye et al., 2022). These situational associations may be particularly interesting as they enhance our understanding of job performance fluctuations at work, providing critical tackling points for workplace interventions. Cognitive functioning domains may be promoted by different interventions (e.g., resource mobilization through exposure to challenge stressors or resource restoration through recovery). Hence, detailed insights into these within-person associations could allow for targeted interventions at work to maximize performance in different work situations (e.g., training situations). Similarly, some cognitive functioning domains may be particularly relevant for certain jobs or positions (e.g., working memory and processing speed may be particularly relevant for jobs that require working at a fast pace, and executive functioning may be particularly relevant for positions that emphasize planning and decision-making). Empirical insights into such associations may allow employers to select the most effective intervention measures for a particular professional group.

Furthermore, additional empirical insights into within-person associations between cognitive functioning and job performance would allow us to disentangle the effects of work demands and recovery on objectively measured cognitive functioning and employee experiences (Sonnentag et al., 2017). As cognitive functioning is a more proximate outcome, it could enrich load and recovery research by providing insights into immediate substantial effects that may be unconscious, fade over time, or be masked by third variable effects, and thus, may only partly translate into conscious experiences (Sonnentag & Geurts, 2009). Investigating cognitive functioning as a mediator in the relationship of work demands and recovery with employee well-being and job performance may critically enhance our understanding of the underlying mechanisms of fluctuating job performance. This approach could be extended to other resources (e.g., emotional resources) to identify parallel or predominant associations (de Jonge & Dormann, 2003), increasing our understanding of "the 'black box' of resource dynamics" (M. A. LePine, 2022, p. 245) in the CHSF.

Recovery and Cognitive Functioning. Although this dissertation extensively investigated the relationship between recovery and cognitive functioning, important research questions remain unanswered. This dissertation has a strong focus on temporal aspects of recovery. However, it may be particularly interesting to investigate quantitative and qualitative recovery in combination (as suggested by the ERM; Meijman & Mulder, 1998).

Comprehensive research approaches considering both quantitative and qualitative recovery may improve our theoretical understanding of recovery and allow for more effective interventions by making simple adjustments regarding their duration or clever choices regarding their timing. Building upon the experimental study of Bennett et al. (2020) focusing on a student sample, occupational diary studies may provide fruitful insights into the optimal combination of recovery activities, experiences, and environments on the one hand and recovery duration on the other. For example, this could provide critical insights into optimal recovery activities to optimize the recovery of employees with fixed break times and environments. Additionally, this could provide interesting information about the optimal timing and duration of a specific recovery intervention.

Furthermore, to enhance the theoretical understanding of recovery processes, future research should further examine the relationships between psychological, physiological, and behavioral recovery outcomes and of recovery activities, experiences, and environments with those outcomes. The findings of this dissertation suggest that psychological (evening fatigue trajectory) and physiological recovery (evening HRV trajectory) may be underlying mechanisms of behavioral recovery (next-morning cognitive functioning; Sonnentag & Geurts, 2009). Building upon these results, it could be interesting to investigate if psychological and physiological recovery are observed in parallel or successively, when and how psychological and physiological recovery translate into cognitive functioning, and which recovery experiences promote primarily psychological or physiological recovery.

As employers have much more influence on employees' work domain than private domain, the role of recovery during work breaks as a critical tackling point to counteract accumulating load should be further stressed in research. Hence, the interplay of different recovery periods could be a fruitful area of investigation (Sonnentag et al., 2017). Recovery opportunities during breaks at work may allow employees to catch up on missed recovery opportunities or even facilitate recovery in following recovery periods (e.g., evening after work; de Bloom et al., 2015; Geurts & Sonnentag, 2006). For example, microbreaks might compensate for a short lunch break on days packed with meetings, restricting employees' break autonomy at lunchtime. Additionally, break recovery might compensate for a lack of recovery experienced at the previous evening or weekend, which may be particularly relevant for employees with care duties (Ericsson et al., 2021). Hence, insights into the interplay of consecutive recovery periods would not only improve our understanding of accumulating load processes but could also be of high relevance for practice.

Environments and Cognitive Functioning. Research on environmental aspects linked to work and recovery may shed further light on the load processes postulated by the ERM (Meijman & Mulder, 1998). Despite affecting job performance and well-being (e.g., Vahey et al., 2004), work environments are often neglected in I/O psychology research, focusing mainly on the effects of task demands. Similarly, the role of recovery environments is rarely investigated in occupational health psychology research, focusing mainly on recovery activities and experiences (Hilbert et al., 2024; for exceptions, see Korpela et al., 2015). However, due to facilitating the restoration of cognitive resources (Kaplan, 1995), environmental aspects may be highly relevant when aiming to maintain and promote cognitive functioning at work.

To gain comprehensive insights into the associations between environmental aspects and cognitive functioning at work, the adapted DSST and SART should be combined with self-report questionnaires on structural organization at work (e.g., administrative processes), objective visual characteristics of the environment (e.g., artificial intelligence extracting the proportion of green from smartphone images), and temperature measurements (e.g., recorded by smartwatches; Felgueiras et al., 2022; Korpela et al., 2015; Vahey et al., 2004). Research on the associations of work and recovery environments with momentary cognitive functioning at work, as well as their interplay with work demands and recovery experiences or durations, could provide valuable practical implications for workplace interventions. Interventions based on work environments may be particularly effective, as changes in environmental aspects (e.g., adding plants to the cafeteria, adapting the temperature or air quality in office spaces, providing adequate administrative support) affect many employees (Felgueiras et al., 2022; Korpela et al., 2015; Vahey et al., 2004).

Additional Application Contexts

Future research should expand the empirical evidence on short-term mental load effects demonstrated in this dissertation to the mid- and long-term effects to provide valuable insights for interventions aiming to sustainably promote employees' work potential, health, and well-being. The empirical studies included in this dissertation focus on short-term effects with assessment periods ranging from three days to two weeks and within-person associations within one day. Applying the cognitive performance tests in diary studies with longer assessment periods would provide empirical evidence on systematic fluctuations in cognitive functioning across longer time periods. Such study designs could capture accumulating or seasonal changes in cognitive functioning, such as accumulating load in teachers between consecutive school holidays or changes in female employees' cognitive functioning across their menstrual cycle. Additionally, measurement burst designs (Sliwinski, 2008), for example, spanning several years with one two-week diary study per year, may allow for the interpretation of long-term changes in cognitive functioning itself but also in cognitive reactivity to work demands, providing valuable insights into cognitive changes across professional careers.

Furthermore, research fields beyond I/O psychology should apply the adapted cognitive performance tests in diary studies, as comprehensive insights into momentary cognitive functioning in diverse real-life situations may enhance our understanding of momentary cognitive functioning fluctuations and allow for the derivation of effective intervention measures. Cognitive functioning is not only highly relevant for occupational functioning but also for human functioning in many life domains, for example, at school or in private life (Cambridge et al., 2018). Hence, several research fields acknowledging the relevance of cognitive functioning may benefit from the application of short smartphone-based cognitive performance tests in diary studies. For example, research fields linked to aging (Salthouse, 2012) or shift work (Leso et al., 2021) may complement prior cross-sectional and longitudinal research on cognitive functioning, with diary studies providing insights into short-term fluctuations and within-person associations (Moore et al., 2017). Furthermore, research fields such as cognitive psychology (Young & Stanton, 2002), environmental psychology (Berto, 2014), or sports sciences (Chang et al., 2012; Gilson et al., 2023) may complement their research on maximum cognitive functioning gained under standardized conditions in experimental or intervention studies with insights into typical cognitive functioning in real-life situations (Trull & Ebner-Priemer, 2013).

Conclusion

Overall, by introducing the 90-second smartphone-based DSST and SART, this dissertation provides the tools to reliably and validly capture momentary cognitive functioning in real-life (work) situations. The two exemplary applications of the adapted cognitive performance tests in occupational diary studies demonstrate their feasibility for objectively measuring employees' momentary performance capacity at work and their utility as a viable alternative to measuring job performance.

Supporting the theoretical assumptions of the ERM (Meijman & Mulder, 1998) and the CHSF (M. A. LePine, 2022), the empirical findings featured in this dissertation suggest positive associations of challenge stressors (Study 2) and evening recovery (Study 3) with cognitive functioning at work. Furthermore, lunch break recovery was identified as a critical boundary condition maintaining resource-mobilizing and counteracting resource-depleting effects of challenge stressors at work (Study 2). These findings underscore that combining self-report questionnaires with objective measurements of momentary cognitive functioning can yield not only methodological but also theoretical and practical contributions.

To maintain employee cognitive functioning throughout the workday, employers should promote employee recovery, for example, by ensuring adequate lunch break durations and facilitating immediate detachment after work. Against the backdrop of prioritizing recovery, fostering challenge appraisals of work demands and scheduling challenging tasks at the beginning of the workday may be associated with sustainable cognitive functioning gains throughout the workday. I hope that my dissertation will encourage researchers in occupational health psychology and beyond to use the adapted cognitive performance tests in their diary studies to benefit from their multifaceted advantages.

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