The Relationship between Pedestrian Density, Walking Speed and Psychological Stress: Examining Physiological Arousal in Crowded Situations

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Abstract

Due to the steadily growing world population and mobility shift, more and more people are moving around in public spaces, such as in train stations or shopping arcades. This increased volume of people has led to restrictions on the functionality of traffic infrastructures. At the same time, it is assumed that the increased pedestrian traffic creates a higher stress load on environmental structures. The Pedestrian Level of Service (PLOS) is an engineering concept and measure that evaluates the functionality and quality of transport infrastructures in relation to density and comfort of movement. Based on a fundamental diagram, this concept assumes reduced quality for pedestrians when there are higher pedestrian traffic densities and associated reduced walking speeds. However, the state of research shows, that researchers have not comprehensively explored the effects of density and reduced speed on pedestrians' stress levels. This work used psychological theories and methods to advance knowledge about the experience of density and speed and how they are related, using measurements of electrodermal activity and subjective ratings to assess stress levels.

This research consisted of four studies that examined different states (walking and standing/waiting) of pedestrians in traffic infrastructures. Studies 1 and 2 explored standing and waiting in dense situations. Study 3 explored walking at different preset and freely chosen walking speeds. Study 4 extended the previous studies to examine the relationship between density and walking speed. It shows that both density and walking speed, when considered separately, do not directly affect physiological stress levels but they do affect participants' subjective ratings. However, the combination of these two parameters showed that walking speed reduced by density leads to increased physiological arousal.

These results provide empirical evidence for the PLOS assumption that the stress of pedestrians increases with increasing density—but only when pedestrians are moving. When considering density while standing/waiting, however, the findings indicate that other factors also influence the stress experience.

Zusammenfassung

Durch die stetig wachsende Weltbevölkerung und die Mobilitätswende bewegen sich immer mehr Menschen im öffentlichen Raum, wie zum Beispiel an Bahnhöfen oder in Einkaufspassagen. Das erhöhte Menschenaufkommen führt zu Einschränkung der Funktionalität der Verkehrsinfrastrukturen. Gleichzeitig wird aber auch eine höhere Stressbelastung der Fußgänger:innen in diesen Strukturen vermutet. Eine ingenieurwissenschaftliche Möglichkeit, Funktionalität und Qualität von Verkehrsinfrastrukturen in Abhängigkeit von Dichte und Bewegungskomfort zu bewerten, sind Pedestrian Level of Service (PLOS) Konzepte. Beruhend auf dem Fundamental Diagramm gehen diese Konzepte von einer reduzierten Qualität für die Fußgänger:innen aus, wenn es zu höheren Dichten und damit einhergehend reduzierten Geschwindigkeiten kommt. Der Stand der Forschung über die Auswirkungen von Dichte und reduzierter Geschwindigkeit auf die Stresswerte von Fußgänger:innen ist allerdings noch nicht ausreichend erforscht. Die Arbeit nutzt psychologische Theorien und Methoden, um das Wissen über das Erleben von Dichte und Geschwindigkeit und deren Zusammenhang zu erweitern. Zur Erfassung von Stress finden die Messung der elektrodermalen Aktivität und subjektive Ratings Verwendung.

Die Arbeit besteht aus vier Studien, die verschiedene Zustände (in Bewegung und stehend / wartend) von Fußgänger:innen in Verkehrsinfrastrukturen untersuchen. Studien 1 und 2 befassen sich mit dem Stehen und Warten in dichten Situationen. Studie 3 betrachtet das Gehen in verschiedenen vorgegebenen und freigewählten Gehgeschwindigkeiten. Studie 4 erweitert die vorherigen Studien, um den Zusammenhang zwischen Dichte und Geschwindigkeit zu untersuchen. Dabei zeigt sich, dass sowohl Dichte als auch Geschwindigkeit als separat betrachtete Faktoren keinen direkten Einfluss auf die physiologischen Stresswerte aber auf die subjektive Bewertung der Versuchspersonen haben. Die Kombination dieser beiden Parameter zeigt allerdings, dass eine durch Dichte reduzierte Geschwindigkeit zu erhöhter physiologischer Erregung führt.

Diese Ergebnisse liefern empirische Evidenz für die Annahme der PLOS, dass die Belastung von Fußgänger:innen bei zunehmender Dichte steigt – allerdings nur bei Bewegung. Die Ergebnisse der reinen Betrachtung von Dichte beim Warten deuten hingegen darauf hin, dass hierbei auch andere Faktoren einen Einfluss auf das Stresserleben haben.

Table of Contents

Acknowledge

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In conclusion, all that remains is to say, "The train pulls in, the train stops, the doors open. The doors close, the train moves off."

List of Abbreviations

µS .... *Microsiemens*
APA.. *American Psychological Association*
BMBF...*German Federal Ministry of Education and Research*
CroMa............................*BMBF-Project "CroMa- Crowd Management in Transport Infrastructures"*
DGPs...*German Psychological Society*
EDA.. *Electrodermal activity, Electrodermal activity*
HR...*Heart rate*
HRV..*Heart rate variablilty*
HRVLF .... *Heart rate varibality low frequency*
LOS .... *Level of service*
NS.SCR... *Non-specific skin conductance*
PLOS ....*Pedestrian level of service*
SC ....*Skin conductance*
SCL.. *Skin conductance level*
SCR ....*Skin condutance response*

List of Figures

List of Tables

1 Introduction

1.1 Outline

Being in crowds is part of our daily life. Sometimes we find ourselves in groups of people we know and with whom we share a socially influenced motivation, such as at demonstrations or in the university lecture hall. But often we unintentionally find ourselves in crowds, at the train station, or while Christmas shopping at the mall, for example. Changing living conditions, such as people's increased mobility, lead us more and more frequently into situations where we are part of a crowd. But exceptional situations, such as the crowd disaster at the Love Parade 2010 show that there is currently insufficient knowledge and theoretical background regarding the field of crowd behavior. Thus, the field is attracting more and more research interest. In this context, the available research has shown that an approach oriented towards only one scientific discipline is not sufficient for discussing and explaining crowd behavior. Since a combination of diverse aspects underlies crowd behavior, it is useful to focus on it from different scientific perspectives that span the fields of physics, mathematics, engineering, and computer science. Crowd behavior is a form of human behavior; therefore, evaluating human experiences and subjective perspectives is an important aspect of understanding crowds. It is clear, then, that psychology is an important discipline in this context, and in recent years, the study of crowd psychology has received more attention.

Density is a central parameter used to describe crowds across various disciplines. In engineering, Density, among other terms, describes the capacity and function of transportation infrastructure within the context of the Pedestrian Level of Service (PLOS) concept/measure. This concept describes a decreasing functionality with increasing density, which results in a reduced quality of experience for pedestrians. In psychology, crowding research examines the relationship between density and the experience of density, especially the associated amount of arousal. This field of research took hold in the 1980s and considers the effects of both long-term stays (waiting periods) in dense areas, such as densely populated urban areas, and short-term stays in crowded situations, which arise from spatial confinement or the lack of distance between people. These investigations have focused on subjective perceptions and behavioral changes due to crowding. The collection of stress parameters, such as physiological arousal, arising as a direct result of being in a crowding situation has not been the main interest in these studies, possibly due to the lack of valid measurement methods. In recent years, however, advances in technology have enabled the collection of physiological parameters in ambulatory settings; this has facilitated the examination of pedestrians in crowds.

The research presented in this thesis aimed to obtain a more comprehensive understanding of the experience of density in crowds by combining knowledge from psychology and engineering science. The focus was on investigating the effects of density on the stress level of individuals in different states of motion (walking and waiting), in public spaces. The research used questionnaires and physiological arousal measurements of electrodermal activity to capture the stress experience. Four studies were conducted to investigate the relationships between stress, density, and walking.

Studies 1 and 2 examined the relationship between stress and density while waiting. The stress levels of subjects waiting in a 1 m^2 box with different numbers of other people were measured. The waiting time varied between the two studies. The goal of these studies was to investigate whether there is a correlation between density and stress in waiting (standing) individuals. The main hypothesis of these studies was that waiting is more stressful at higher densities. The results of Studies 1 and 2 showed that there was no increase in objective stress parameters with increasing density during waiting. However, the subjective evaluations of the subjects indicated denser as more unpleasant.

When walking in crowds, pedestrians repeatedly have to reduce their walking speeds and adapt to the situation. Reduced speed and lack of opportunities to overtake are central aspects of the PLOS. Therefore, Study 3 focused on the relationship between stress and motion. The study had two main objectives: The first was to gain a better understanding of the effects of walking on electrodermal activity (EDA) measurements. The second was to investigate the influence of the discrepancy between the desired walking speed and the forcibly reduced walking speed. The lack of opportunity to overtake was also considered. The hypothesis was that forcing people to walk slowly would lead to an increase in stress parameters and that the desire to overtake would influence stress values due to impatience. The results showed that faster walking led to increased physiological arousal and thus higher EDA values, while subjects perceived slow walking as more unpleasant. Ultimately, the discrepancy between the desired and reduced walking speeds had no impact on physiological stress levels but did impact the subjective perceptions of the subjects.

As the reduction of walking speed in crowds is accompanied by an increase in density, Study 4 was a complement to Study 3, and examined the relationship between stress, density, and walking. The stress levels of subjects walking at a reduced speed due to increasing density were measured. A single-file experiment that replicated the relationship between speed and density from the fundamental diagram, examined this relationship. The hypothesis was that increasing density and thus slower walking speeds lead to an increase in stress parameters. The results of this study confirmed that increased density led to increased stress parameters.

In summary, this research provides important insights into the correlations between stress, density, and motion, and thus, it improves our understanding of the crowd experience in transportation infrastructures. The findings contribute to developing better strategies for managing crowds and improving the overall transportation experience.

1.2 Structure of the Thesis

In this thesis, Chapter 2 provides an overview of the state of the research into crowd behavior and the overlap between the engineering Pedestrian Level of Service (PLOS) concept and psychological theories of crowding. In addition, the chapter provides insight into psychological stress research, the elicitation of stress using electrodermal activity (EDA) and using subjective ratings as measurement tools to capture stress. Chapter 2 concludes by defining the substantive issues of this thesis. Chapter 3 reviews research on the use of the EDA method. It explains the used measurement parameters and algorithms. Chapter 4 presents the empirical framework of the explorative studies conducted to examine a defined hypothesis concerning the relationship between the factors. This chapter describes the different density concepts and explains how they were operationalized in the studies. Chapter 5 and 6 presents the setup of the experiments and describes the results. Since this thesis is located at a little-explored interface of pedestrian research, which takes both an engineering perspective and focuses on the psychology of crowding, it has the potential to make further conceptual deductions based on an interdisciplinary perspective. Therefore, Chapter 7 revisits the results of the studies and places them in a larger overall context. In doing so, the thesis concludes by raising further research questions that will ultimately allow for a more comprehensive picture of what happens concerning the arousal of individuals in dense situations.

2 Theoretical Background

This chapter first outlines the established connection between the Pedestrian Level of Service concept initially developed by Fruin (1971) and extended by Weidmann (1993), and personal space and crowding concepts from the perspective of psychology. This theory chapter thereby introduces an engineering perspective to social, environmental, and biopsychological perspectives to derive the research questions and methods of this thesis. A discussion of the term stress and an explanation of how subjective and objective survey methods can measured stress follows. Current research on the topic of density and its subjective perceptions and how it is related to physiological arousal is then presented before the research questions are described.

2.1 Pedestrian Level of Service (PLOS)

A well-established engineering method for studying the quality of transportation systems is the Level of Service (LOS) (Transportation Research, 2016). The LOS is a qualitative measurement tool from the field of engineering science that determines the quality of motorized vehicle traffic. The concept evaluates traffic in different categories (A to F) depending on its density and speed (Transportation Research, 2016). Higher categories indicated higher traffic volumes and lower travel speeds (flow) and lead to a worse evaluation of the transport system. The LOS is a tool for road planning and traffic congestion analysis. It has been extended in the form of the Pedestrian Level of Service (PLOS) to consider the quality of pedestrians traffic (Landis et al., 2001).

Research into the LOS dates back several decades (Holl, 2016). Based on the “Fire Safety in Theaters” guidelines published by Dieckmann (1911), Fischer (1933) considered the throughput of people at doors as a function of their width and the throughput speed of passage as a function of the width of the traffic route. Riemer (1947) published the first work on the relationship between flow, velocity, and density, borrowing the concept from Greenshields’ fundamental diagram for motorized traffic (Greenshields, 1934, 1935). Scholz (1952) studied not only the fundamentals of movement but also the requirements for traffic facilities while Oeding (1963) first added quality levels to measure the quality of traffic. Fruin (1971) then developed the PLOS based on Riemer’s (1947) fundamental diagram, which was based on data collected from observational studies. The fundamental diagram describes the transport properties of passenger flows. It allows linking the flow, as a measure of performance, with the density. The PLOS assigns a comfort level to the density value. So, in practice, it means that the fundamental diagram assigns a density to the flow value of the passenger flow, for example at a platform. From this density the PLOS then estimates the comfort level. Regarding the theoretical development of the PLOS, Weidmann (1993) established categories to assess the criteria of the quality of the pedestrian facility, these included aspects of movements, like e.g. the possibility of free speed selection and restriction on overtaking. But also, the necessity to pay attention to other pedestrians and the frequency of unwanted physical contacts. Since the PLOS is based on the fundamental diagram, its quality levels are always a function of density. Weidmann's (1993) criteria also generate higher scores when density increased.

Oeding (1963), Pushkarev and Zupan (1975), and Schnabel and Lohse (1980) define density as people per square meter. However, Fruin (1971) saw density not only as people per square meter but also as the area available per person. He also developed a PLOS, which assessed for waiting areas, again assessing quality as a function of available space. Overall, engineering assessments of the quality of pedestrian facilities are about objective quality. From the point of view of psychology, however, the subjective experience of the different quality levels of the level of service is also interesting, as is the effect on objective stress parameters, as measured by physiological arousal. The correspondence between the assessments of the engineering scientists and the subjective and objective stress levels as measured in humans should be investigated and the triggering factors should be considered. In this context, it is relevant to examine the parameters of the fundamental diagram (density and speed) as individual factors on the stress experiences of pedestrians and consider the effect of the combination of the two parameters on stress values, to better understand individuals' experiences of dense situations.

Overall, the PLOS seeks to better understand and explain the movement of people in crowds. For this purpose, Fruin (1971, 1987) explained individual space requirements and the ability of people to move. For this, Fruin drew on Hall's (1969) proxemics principle and integrated it as the "personal body buffer zone." This concept assumes that people have a certain claim on space. Hall's understanding of personal space includes the existence of distance zones around a person's body. He divided a person's environment into four distance zones: public, social, personal, and intimate. Specific groups can only enter the different zones (see Figure 1) without causing discomfort for the person. Hall determined radii for the individual distance zones. However, these are not rigid, and perceptions of distance and space depend, for example, on cultural background influences, as well as other factors (Cochran et al., 1984; Sommer, 2002).

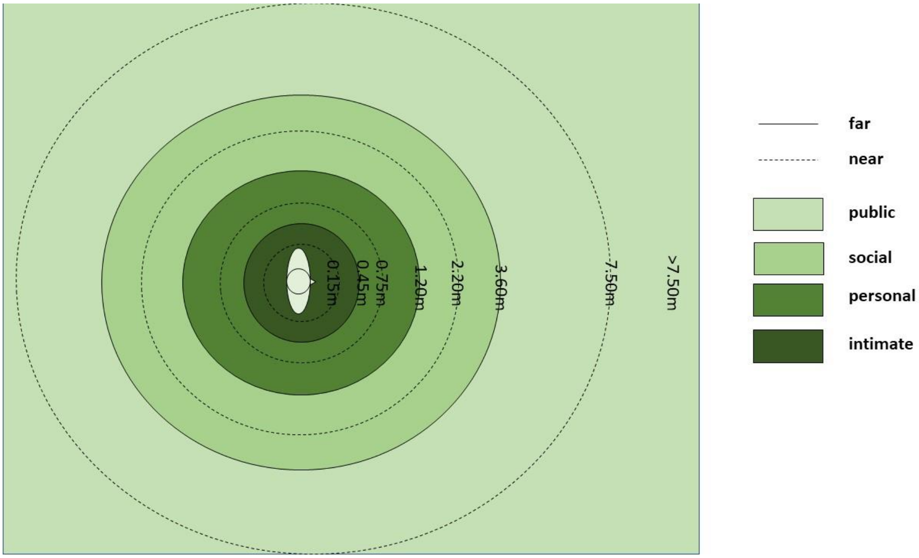


Figure 1: Distance zones according to Hall (1969).

While Fruin (1971) looked at Hall's (1969) concept and the personal body buffer zone mainly from the perspective of movement in crowds, a line of research has developed in psychology that examines how individuals experience density and confinement, and accordingly, personal space. The field of research is commonly referred to as crowding research.

2.2 Crowding Research

The term crowding is broad and includes all kinds of phenomena around the experience of density and constriction. Research on this phenomenon may concern social coexistence, such as living in highly populated neighborhoods (Gillis, 1979) or global overpopulation (Epstein, 1981). Furthermore, the experience of waiting or traveling in high densities, such as in crowds or trains in daily life, belongs to this field of research (Cox et al., 2006). In this thesis, the focus was on the effects of short-term density stays, such as being in crowds of individuals.

Pedestrian dynamics research often refers to crowd psychology, which has a social psychological focus on crowds (Drury, 2014; Reicher, 2001). Original research into crowding by Le Bon (2002), Freud (1921), and Sighele (2019) focused mainly on violent crowd behavior in terms of riots (Drury, 2020). Lately, a more comprehensive view of crowds has developed where the primary focus is on psychological crowds and concepts such as collective behavior. Psychological crowds are crowds with a common goal or identity, such as people at demonstrations (Adrian et al., 2019). A central theory of crowd psychology is Reicher and Drury's (2016) self-categorization theory. Under this theory, they explained crowd behaviors in terms of feelings of group membership. In addition, Templeton et al. (2018) found a difference in spacing when walking together in a group between groups with a shared identity and those without a shared identity. Furthermore, Novelli et al. (2010) found that belonging to the same group led subjects to walk at a closer distance to their interaction partners compared to when the interaction partner belonged to a different group. These studies show the effect of social identity on personal space. However, while these research results are interesting, they do not consider the experience of dense situations in public spaces. Physical crowds are found mostly in public spaces and occur when a larger number of people are in the same place at the same time and do not have a common identity (Adrian et al., 2019). To gain a more profound understanding of physical crowds, gaining an individual perspective on the experience of density is a purposeful starting point. This is the perspective of crowding research. Crowding research focuses on the individual and his or her subjective experience of being crowded in different contexts (Strohmer & Wirtz, 2021).

Researchers coined the term “crowding research” as early as the 1970s. During this time, a whole series of works on this topic has been published (Roskamm, 2011; Vine, 1981, 1982). It is important to note that the term crowding research is used in psychological, sociological, architectural, and urban planning. Thus, recent works can be found on the effects of living in confined spaces (Husemann, 2005) or the perception of space in urban tourist contexts (Lin et al., 2023; Neuts & Nijkamp, 2011; Neuts & Vanneste, 2018). In this work, the focus was on the experience of density and confinement in crowds that do not have a common goal and on the individual short-term experiences of being in this state and their effects. Stress and load (Roskamm, 2011; Vine, 1981, 1982) were used to describe the effect of crowding.

In science, it is important to distinguish between the terms crowding and density. In the past, the terms density and crowding have often been used interchangeably (Stokols, 1972). This implies, however, that any dense situation would lead to an experience of crowding. Based on Stokols’s (1972 model, density is now seen as a trigger for crowding (Saegert, 1978)—along with other factors that are more social in nature, personality-dependent, or environmental (Vine, 1982). Thus, density is a central element in crowding research. To adequately assess previous studies and current theories, I first look at the definition of density, before considering theories on and explanatory approaches to the phenomena of crowding.

2.2.1 Density

The field of crowding research made a distinction between physical and social density. Social density is seen as the number of people in a specified area measured by the unit of people per m²

(*Crowding*, 2014)). Hence, to increase social density, the amount of people in the same area increased. Meanwhile, the physical density is determined by the area available per person (*Crowding*, 2014). Thus, a decrease in density takes place by increasing the physical space around a person. The limiting factors of physical space do not necessarily have to be objects or walls; they can also be other people (Roskamm, 2011). In pedestrian dynamics research, both types of density definitions can be found (Adrian et al., 2019). For example, Fruin (1971) and Weidmann (1993) provide both physical density and social density categories in their PLOS. Overall, the physical density specification is a definition centered on the individual that indicates how much space is available for the individual's space claim and, consequently, according to Hall (1969), which distance zones of personal space may have been violated. When specifying physical density, the space available to individuals must be considered to make estimates about the violation of personal space.

2.2.2 Personal space

Psychology describes personal space as "an area or territory that directly concerns one's own body and plays an important regulating role in the interaction with others. It acts as an invisible protection…" (Hellbrück & Kals, 2012, p. 78), translated). The concept of personal space, along with that of distance behavior, was first introduced by Katz in the 1930s. Based on animal studies, Katz (1937) found that animals have an individual claim to space and defend it. This concept also applies to humans. In scientific discussions, there is no unanimous opinion about the nature of personal space. For some researchers (Vine, 1982), personal space possesses a rigid border that cannot be penetrated by the environment. However, some situations in our everyday lives, such as intimacy or even doctor's appointments, contradict this argument. Hall's (1969) concept of border, which may be violated by different persons with different relationship statuses, seems more plausible here. While Hall, in simplified terms, imagines personal space as a simple cylinder, it also carries the notion of an envelope metaphor (Hellbrück & Kals, 2012). Under this notion, personal space surrounds individuals like a second skin with a certain fixed distance. Despite disagreement about the form of personal space, the unified opinion is that unwanted violations lead to internal discomfort or stress (Hall, 1969; Hayduk, 1978; Vine, 1982; Worchel & Teddlie, 1976). A criticism of this assumption regards the difficulty of validating inner discomfort as a psychological process (Vine, 1982). This thesis addressed this problem. One way to capture inner discomfort is to elicit a stress experience. In the theories described below, stress experience is also a central indicator and a consequence of crowding.

2.2.3 Theories on the emergence of crowding stress

2.2.3.1 Two-factor theory of crowding

The basic assumptions of Worchel and Teddlie's (1976) two-factor theory of crowding are that the personal domain violations associated with crowding lead to physiological arousal such as a faster heartbeat (physiological arousal is described in Chapter 2.4.2). This initial arousal must then be associated with the presence of the crowd. Interestingly, these authors include an atemporal component when they refer to initial arousal. They assumed that behavioral change is compensation for this arousal and may lead to withdrawal or hostile behavior. This theory also explains the aversive reaction to unwanted approaches. Stokols (1976, 1978) postulates that approaches by strangers that are perceived as intended lead to more aversive reactions than approaches that are perceived as unintended. One reason for this is that we perceive intended intrusion into our personal space as an invasion of our privacy and personality and as a potential threat.

Behavioral studies of personal space

It must be noted that to date, the studies on personal space have been insufficient and limited in their resources. A list of studies can be found in Sommer (2002). In summary, studies on the violation of personal space from the 1980s were technically limited as far as the methodologies for collecting indicators were concerned, but also because of ethical problems in defining the study designs as well as implementation problems. Researcher commonly divided the studies into two types: field and laboratory studies. Field observations were distinguished into naturalistic and manipulated settings. Thus, Schiavo et al. (1995) and Ruback and Snow (1993) created study situations in which investigators placed themselves inappropriately close to subjects while observing their behavior. However, it is questionable here whether the subjects were sufficiently manipulated to elicit a visible response and whether they experienced a deliberate invasion of privacy.

There is also a lack of motion studies in previous work, both in the laboratory and the field. In laboratory studies, paper-and-pencil studies, such as those using the Comfort Interaction Distance Scale (Duke & & Nowicki, 1972; Givon-Benjio et al., 2020; Perry et al., 2013), were often used to investigate the boundaries of personal space (Givon-Benjio et al., 2020; Perry et al., 2013). In this test, subjects see a paper with a person in the middle. Around the person is a circle with another person in it. The subject must imagine themselves as the person in the middle. Then they answer how they feel, depending on whether the person in the circle is a stranger to them or someone they know. A Study from Desor (1972) also uses miniature model rooms in which the subject had to position model subjects, considering whether the distance between them was adequate for a given situation. These types of study allow the personal space to be defined as a function of the setting. However, they are very dependent on the subjects' memory and their perspective imagination. They also lack any social interaction. An alternate laboratory experiment is the approach-stop design (Hayduk, 1978). Here, an unknown experimenter approaches the subject, and when the proximity becomes uncomfortable for the subject, they say "stop." Then the researchers measured the distance between the subject and the experimenter. However, this type of experiment is not very realistic, nor it does not investigate what happens when personal space is undercut; instead, the experiment is aimed at establishing the radius of the personal space.

Physiological studies of personal space

In 1998, Omori and Miyata examined the physiological response to different distances between interviewees during an interview and found higher arousal at shorter distances. More recent research has begun to examine the states operating within the individual in relation to personal space, violation, and crowding. A study by Engelniederhammer et al. (2019) used mobile distance and EDA sensors in front of the chest to measure the effect of violations of a two-meter radius during a walk in Hong Kong and found increased physiological responses at violations to the area two meters in front of the walkers. In another walking study, LaJeunesse et al. (2021) investigated the effect of different environments on physiological arousal as measured by the EDA; locations that were associated with increased crowding, and thus more likely to violate personal space, resulted in higher physiological arousal.

2.2.3.2 Disturbance of goal-directed activity (disturbance hypothesis)

The disturbance hypothesis applies to both social and physical densities (Vine, 1981). Centrally, it is concerned with interference in the performance of current activities or tasks due to the proximity of other people or confined space. Ultimately, resources to achieve goals are restricted and lead to stress and frustration. It is, however, important to keep in mind that density is not generally a problem for any task, but that the associated disturbance affects behavior (Baron & Rodin, 1978; Loo, 1978; Schopler & Stockdale, 1977). Schopler and Stockdale (1977) found that crowding stress was the direct cause of subjective perceptions of crowding due to density and the resulting disruption of a task. Overall, several types of stress resulting from the disruption of goal-directed activity have been identified. Baron and Rodin (1978) distinguish between stress experiences due to loss of decision freedom, numerosity stress, and privacy stress. Stress due to loss of decision-making freedom can also occur independently of other people due to small spaces or even structural conditions. Numerosity stress occurs when particularly arousing social stimuli initiate the disturbance. Disturbance by people who come too close and are thus perceived as a threat to our integrity also generates disturbances and gives rise to privacy stress. Subjects perceived social densities as especially frustrating because of the invasion of privacy by other people. One way to put such intrusions and the associated disturbance of goal-directed activity into perspective is to dehumanize strangers (Bernard et al., 1971). However, they can still be perceived as a physical source of interference and thus interfere with task performance. Stokols (1976, 1978) also reported that if task interference is perceived as intentional, it is significantly more aversive and stress-producing.

2.2.3.3 Social intrusion into the private sphere

Through intrusions into the private social sphere, the likelihood of experiencing uncontrollable social assault increases (Altman I., 1977; Baum, 1978; Baum & Valins, 1977; Bossley M., 1976; Insel & Lindgren, 1978). This theory is most consistent with the two-factor theory of crowding (Worchel & Teddlie, 1976) and also Hall's (Hall, 1969) understanding of personal space. The two-factor theory assumes that each person has a certain "private" area around themself and accessing this private area is not desirable. This spatial hypothesis is supported by Aiello et al. (1977), Edney and Uhlig (1977), and Worchel (1978). However, it also includes other important factors that influence the development of stress, one of which is expectancy. If there is an expectation of high density in a crowd, such as on a train or at a concert, the violation of personal space is not perceived as aggressive, unlike unexpected violations (Goffman, 1971; Karlin et al., 1976).

2.2.3.4 Loss of personal freedom and control

The main idea is that individuals construct their environment in such a way that the maximum number of choices is available and a high level of control is perceived (Proshansky et al., 1970). Studies have shown that the illusion of control alone acts as a protection against stress and reduces the effects of stress triggered by a loss of control (Lazarus & Folkman, 1986; Lefcourt, 1973; Steiner, 1970). Furthermore, having genuine control in crowded situations reduces judgments of the degree of crowding density (Lundberg, 1976).

By looking at all these different theoretical approaches, we can see the main contributors to crowding stress. In addition to the violation of personal space, other factors influencing the experience of stress are obstructions or disruptions in activities due to insufficient space, and the associated threat to one's autonomy and loss of control. However, expectations, social norms, and personal goals also influence the experience of crowding and create crowding stress.

2.3 Stress Models

Crowding is generally assumed to be an indicator of stress experience and load and the impairment of a person's well-being. Evans and Cohen (1978) found that negative affect, anxiety, and signs of nervousness are associated with crowding. In addition, Evans (1979) found poorer performance on complex tasks and increased psychophysiological stress levels in college students when they were situated in higher compared to lower densities (0.89 m^2/person vs. 5.57 m^2/person). Aiello et al. (1977) and D'Atri (1975) also found increased physiological parameters for stress. However, the definition of stress concepts in crowding research is flawed. In the two-factor theory of crowding (Worchel & Teddlie, 1976), it is not stress that is referred to but arousal, and thus, “stress” is viewed from a more biological/physiological perspective. Nevertheless, the theories within this research all follow the understanding that poor coping in a given situation leads to crowding stress (Vine, 1982). The following paragraphs discuss the still-valid stress models; they are also related to the topic under study here, and they define the concept of stress in this thesis.

Stress research is a large field that mainly developed at the same time as crowding research. To date, there is more than one definition of stress in the literature. In medicine, stress is:

> “… a state of the organism that is characterized by a specific syndrome (such as increased sympathetic activity, increased release of catecholamines, increases in blood pressure, and the like) and can be triggered by a variety of stimuli (as well as infections, violations, burns, radiation exposure, but also anger, joy, pressure to perform, and other stressors). Stress can also be understood as an external influence to which the body is not sufficiently adapted, e.g., heat. Psychological stress arises as a result of a discrepancy between specific requirements and subjective coping behavior. Continuous stress can lead to a general reaction in the sense of a general adaptation syndrome.” (Pschyrembel, 1998), pp. 1517f., translated)

Overall, there are many models that define stress, most of which refer to the work context. Common to all stress theories are the factors that describe the stress event. These stressors encompass the conditions and situations to which a person is exposed. Another factor is the stress response to a stressor; this can take the form of both psychological (emotional) and physical (physiological arousal) reactions and personal motives, attitudes, and evaluations are influencing factors. A third component is the consequence of stress. A distinction is made between physiological-somatic (Dawans & Heinrichs, 2017), cognitive, and emotional reactions (anger, rage, frustration) (Lazarus, 1999; Spector & Goh, 2001), and the behavior that accompanies stress. In this context, stress can manifest itself through escape, change of reaction and strategy, or aggressive behavior (Semmer et al., 2010; Zapf & Semmer, 2004). The impact of stress on people’s behaviors and emotions makes it important to learn more about how pedestrian experienced stress in crowds so they can be better assessed, and crowd behavior can be predicted. In the following sections, I present various stress research models, including the biological, sociological, and psychological stress models.

2.3.1 The biological stress model

The physiologist and biologist Seyle (1956) is considered to be the father of stress research. His main focus was on the study of physiological processes when people are confronted with stressors. According to Selye, stressors can be of any kind and nature, and both positive and negative. He distinguished between positive stress (eustress) and negative stress (distress). His central idea was that all non-specific physiological reactions that occur are stress, and the reactions are independent of the type of stressor. However, with this assumption, all stress reactions would have to be identical (Mason, 1975). Seyle (1981) later revised his assumption and described that reactions to demands consist of both a specific and a nonspecific element. For him, only the non-specific element is stress. He also coined the notion of the general adaptation syndrome, which differentiates between three phases of stress adaptation: alarm, resistance, and exhaustion. At the beginning of every stress reaction is the alarm phase; in this phase, the fight or flight reaction occurs (Cannon, 1914), hormones are released, and the physiological reactions of the body occur. In the resistance phase that follows, the body musters the resources to deal with the stressor. The final phase is the exhaustion phase; in this phase, the physical resources to deal with the stressors decrease significantly, and if the stress does not subside, this phase can lead to death.

2.3.2 The sociological stress model

The sociological stress model is a stressor-oriented model (Schwarzer, 2001). It assumes that each stress elicits a specific response and produces an independent behavior as a reaction. Under this model, stressors can have both positive and negative consequences and are thus a resource or a burden. The stimulus-response relationship is important for defining the stress response. Likewise, sociological factors such as support or reinforcement influence the stress experience. According to this understanding, stress results from an imbalance between personal and environmental factors (Haslam et al., 2005). However, different social factors mediated stress responses.

2.3.3 The psychological stress model

The psychological stress model, according to Lazarus and Folkman (1986), is also a stressor-oriented model and is referred to as the transactional stress concept (Struhs-Wehr, 2017). Central to this model is that not every stressor triggers stress in every person. Lazarus and Folkman (1986) explain this as being the individual's internal evaluation of whether they are stressed by a stressor; this evaluation determines whether a stress reaction occurs or not. Therefore, this model also includes the individual's evaluation of the stressor, as well as their reaction to the stress; thus, a stress reaction and its intensity are the results of an internal evaluation. During this evaluation, a person decides whether the stressor is neutral, threatening, or beneficial. If the situation is perceived as threatening, a further distinction is made as to whether it is a challenging situation that can lead to positive stress, or whether it is a threatening, unfavorable situation that might trigger stress and further negative evaluation. Besides stressor evaluation, Lazarus and Folkman (1984) also considers that coping with (or handling) stressful situations is relevant. Coping means that the person experiencing stress intervenes to reduce it. Among other reactions, the individual regulates their emotions, and their physiological reactions are moderated. Subsequently, the situation is re-evaluated, and person change the decision about whether the situation is stressful. A subjective evaluation is the indicator of a stress response to a stressor (Schwarzer, 2001).

Overall, the delineation between the conceptualization and definition of stress is difficult. In general, we can say that stress is present if an individual shows one or more characteristic stress reactions. For Lazarus (1986), physiological stress results from a special relationship between the individual and the environment. Crucial to this relationship is their evaluation of environmental factors. If the individual perceives these factors as exceeding their resources and threatening their well-being, psychological stress occurs. In this thesis, stress is understood as following this psychological model, and measured physiological arousal is taken as the operationalization of stress.

2.4 Methods of Measuring Stress in Research

In psychology, there are various methods to examine stress. A distinction can be made between subjective (self-report) and objective (EDA) methods. The following sections outline these two methods and discuss some density research studies that have used them.

2.4.1 Subjective measures of stress: Self-reports

2.4.1.1 Background on self-reports

Self-reports are a proven method of assessing and evaluating experiences (Bortz & Döring, 2006). They are an economical method of data collection since only paper and pen are needed. In a self-report, people describe or evaluate themselves. They assume that people like to report on themselves and know themselves best. Self-reports are separated into direct, indirect, and free reports (Häcker et al., 2009). In direct reports, items ask individuals directly about the phenomenon of interest. Indirect self-reports are used for more complicated questions that cannot be asked directly. However, when it comes to answering questions about aggressiveness or attitudes, for example, people tend to give socially accepted answers. This is because social desirability, which refers to behavior that is deemed socially acceptable, highly influences such constructs. Thus, social desirability can influence the assessment and lead to bias in the data. Free self-reports typically refer to open-ended questions in questionnaires but can include interviews (Bortz & Döring, 2006).

In conclusion, a lack of objectivity always has to be considered when using self-reports. This also applies to retrospective data because the data correspond exclusively to the respondents' perceptions. These perceptions can be distorted both intentionally and unintentionally. Furthermore, respondents often form hypotheses about what the research question or "desired" answer is. This can lead to the adjustment of their answer (Krumpal, 2013). Predefined answer categories in questionnaires can lead respondents to answer towards the middle of the scale, which means leads to questions about the validity of the answers (Bogner & Landrock, 2015). Despite these issues, self-reports provide information on an individual's state of mind or attitudes, which this method exclusively records. In addition, they reflect internally perceived sensitivities. This means that in relation to perceptions of stress experiences, for example, the internal evaluation processes also directly reflect perceptions of arousal. However, the extent to which a stressor is perceived as positive or negative can only be determined to a limited extent from self-report perceptions of arousal.

2.4.1.2 Subjective stress assessment in the context of density research

In the context of research on density, questionnaires and self-reports capture perceptions of density. For example, when customers were asked to self-report how they experienced density when shopping and perceived the situation, Pons et al. (2016) and (Machleit et al., 2000) reported that high densities lead to an unpleasant shopping experience. Furthermore, a similar study by Whiting and Nakos (2008) showed that experiencing medium densities gives a more pleasant feeling compared to low and high densities. Essentially, this means that the perception of density is weakened when individuals feel more comfortable. However, the design of this study can be criticized for failing to effectively define high and low density. Furthermore, the condition "variation of density" was only subjectively recorded via test subject reports; the researchers did not collect real density values from inside the shops. In contrast, Mowen et al. (2003) showed that low densities were perceived negatively in a festival context, meaning that the festival was not perceived as successful. While these studies had highly situation-specific contexts, they provide an impetus for the possibility of capturing well-being in relation to density via self-reports.

Jia et al. (2022) conducted an experiment that objectively measured densities and collected perceptions via self-reports whereby subjects walk through various narrow passage test setups. By varying the width of the passages, walking speed (measured by trajectory) was affected, and local congestion was created. Jia et al. found that reduced walking speed led to more discomfort than standing in local densities. The authors attributed this to increased discomfort due to the lack of opportunity to walk at the desired or freely chosen walking speed. In accordance with the underlying assumptions of Helbing et al.'s (2000) simulation algorithm, Jia et al. saw the difference between desire and reality as an indicator of the expression of discomfort. However, they disregarded the argument that reduced speeds, as were generated in their study, are always associated with increased density. In their study objects as well as other individuals caused higher density and lower walking speed, which consequently led to a violation of personal space.

2.4.2 Objective measures of stress: Psychophysiological basis

The human body has different nervous systems. A distinction is made between the central nervous system and the autonomic or vegetative nervous system (ANS) (Birbaumer & Schmidt, 2010). The task of the ANS is to maintain vital processes and adaptations to the challenges posed to humans by the environment. To accomplish this, the ANS innervates the internal organs and consists of two components: the sympathetic and parasympathetic nervous systems. These two components often work as antagonists (Schandry, 2016). The sympathetic nervous system has an activating function and is responsible for the "fight or flight" response (Cannon, 1914), which is the basic instinct of survival. Thereby, both fight and flight require an increased capacity of the body (e.g., increased heart or breathing rate) to support the planned behavior: fight or flight. On the contrary, the parasympathetic nervous system has a calming effect (Pham et al., 2021). For example, innervating the parasympathetic nervous system slows the heart rate. Hence, for perceived threatening situations, this sympathetic activation is of considerable interest (Schandry, 2016). Both subsystems innervate most of the body's organs. In psychophysiology, the ANS and its subsystems play a central role. Hence, most methods that measure physiological reactions use ANS responses. This is justified by the very limited possibility of conscious influence on ANS reactions—for example, heartbeat, respiration, and eyelid closure (Gramann & Schandry, 2009)—which are used to measure the reactions of the parasympathetic and sympathetic systems. An exception to this is perspiration because the eccrine glands (sweat glands) are exclusively controlled by the sympathetic nervous system; therefore, electrodermal activity (EDA) is used to measure the activity level of the eccrine glands (Dawson et al., 2017).

2.4.2.1 EDA as an indicator of stress

The body does not only use the sweat response for thermoregulation. The eccrine sweat glands are in the hypodermis, with the highest density in the palms and soles, and are under the control of the sympathetic nervous system. As a consequence sweat from the eccrine sweat glands can be used for EDA measurements (Groscurth, 2002). In general, sweat is a sensitive marker of emotions, stress, and attention (Benoit et al., 2009; Kreibig, 2010; Mavros, 2019). Sweat from eccrine glands is also referred to as mental or emotional sweating (Asahina et al., 2003).

The central control of the eccrine sweat glands is performed by the postganglionic sudomotor neurons, which belong to the lateral chain of the sympathetic nervous system (Jänig & Kümmel, 1981). These lead directly to the intermediolateral nucleus via the spinal cord and thus are subject to the neuronal circuitry of the sympathetic nervous system. Imaging studies have shown that activity in the hypothalamus, limbic system, amygdala, and cortical frontal area (PFC) are related to EDA measurement differences (Lee et al., 1988; Mangina & Beuzeron-Mangina, 1996; Zahn, Grafman, & Tranel, 1999). Overall, the literature suggests that the EDA has physiological access to higher-level cognitive components that are dependent on the influence of reticular, limbic, and cortical areas, such as emotions and stress (Sequeira et al., 2009).

2.4.2.2 EDA in the field

In psychology laboratory research, EDA measurement is used to assess stress. It is also frequently used in studies of traffic psychology (Affanni et al., 2018; Benoit et al., 2009; Bigazzi et al., 2022; Dehzangi et al., 2018; Helander, 1978; Li et al., 2022; Mavros, 2019; Zontone et al., 2019). For example, drivers have been exposed to various stress-inducing situations and examined for stress reactions (Affanni et al., 2018), and also for attention (Aminosharieh Najafi et al., 2023). From a measurement perspective, it is advantageous that driving cars is done in a sitting position and that there is enough space available to use larger measurement devices. Thus, EDA was introduced as an early measurement method for stationary experimental setups in traffic psychology (e. g. Helander, (1978)).

The use of EDA is also becoming increasingly popular in travel psychology research. A meta-analysis by Bigazzi et al. (2022) summarizes the studies on active travel. It is noticeable that the most common studies are those with bicycles. These examine, for example, whether the presence of bicycle paths lowers stress levels. Next to bicycle research, research has focused on pedestrians in traffic situations; those that focus on movement used EDA as a measurement tool in the field as well as in the laboratory. Other studies have different foci. For example, some have focused on the cognitive load of travelers. For example, Armougum et al. (2020; 2019) conducted two studies, one virtual reality study and one in a real-life context. They found that traveler expertise lowers cognitive load in information processing and that infrequent travelers experience more cognitive load than commuters. Furthermore, Mudassar et al. (2021) investigated the relationship between stress and crossing roads in a virtual reality case study. They found that the closer a car is to a pedestrian crossing the road, the higher their stress levels are. Electrodermal activity has already been used in studies of urban experience contexts (Mavros, 2019; Schrenk et al., 2009). For example, Chrisinger and King (2018) examined stressful areas within a neighborhood during a walk.

2.4.2.3 EDA and density

In this section, I take a closer look at studies that have examined the influence of physical proximity of other people, density, and EDA. These studies fall into two categories: naturalistic field studies in which subjects take a walk, and quasi-laboratory studies in which subjects engage in an experimental setup under controlled conditions.

A field study by Engelniederhammer et al. (2019) used EDA as an indicator of stress response to the violation of a two-meter personal distance space (in front of the subject) in the city of Hong Kong. They conducted this study using a chest sensor, which detected the intrusion of other people into the two-meter radius. They found a short-lived increase in EDA levels directly after the intrusion. It was concluded that violation of the two-meter distance led to increased stress levels. The researchers also found that different path distances led to different responses as a function of density, with higher density distances associated with more stress.

LaJeunesse et al. (2021) conducted a study on the impact of crosswalks in different environments on stress levels. They had their subjects walk through different neighborhoods on Capitol Hill in the United States. They found that neighborhoods associated with higher densities, such as shopping streets or places where there are many office buildings, are associated with higher stress levels.

Mavros et al. (2022) conducted a video treadmill study on crowding experience in the context of different environments. Surprisingly, they found that subjects experience urban outdoor environments as less stressful than indoor environments when walking forward, regardless of how crowded the video scenarios were. In addition, the indoor condition subjects showed higher stress levels when walking in overcrowded situations. The study also strongly suggested that pedestrian perceive outdoor crowded situations as less stressful than indoor ones; subjectively, subjects perceived crowded outdoor scenarios to be the least stressful. In the study, there was no physical proximity to other people, but the situations were simulated solely through the presentation of videos. In contrast, studies by Armougum et al. (2020; 2019) have shown that virtual reality is a potential was to examine stress in real contexts. This highlights the need to develop a more profound understanding of the perception of crowding.

In a study by Zhao et al. (2019), the social repulsion force of people in different experimental setups was investigated. The first experimental setup examined the reactions of people walking through a crowd (as represented by two people). The “crowd” around the subject resulted in a measurable increase in stress parameters immediately after they walked by it. There was a clear reaction in the subject from the passing and the proximity of the other person. Furthermore, in the face-to-face condition, i.e., when the crowd looked towards the subject, a more significant stress parameter response was measured than when the subject passed the crowd from behind (i.e., without face-to-face contact). The second experimental setup studied the passing of several people in a corridor, one after the other. Here, the EDA stress parameters increased after the subject reached the corridor and shortly after they passed through people, generated by the narrowing of the corridor. In tests with blind individuals only the physical contact with another individual led to an increase in EDA activity. From this, I assumed that the visually perceived violation of personal space or someone entering one’s physical space always led to stress and result in increased EDA levels. However, the exact relationships underlying the specific crowd conditions that lead to stress are not yet clear. For example, a study by Szpak et al. (2015) showed that the social proximity of strangers in tasks done while stationary at a table was only perceived as uncomfortable if the task had previously been done alone at the table. This raises questions about whether the expectation of the situation or the flexibility and size of the personal space area plays a decisive role in the stress response.

In conclusion, we can say that capturing the impact of density on people using EDA measurement is possible. However, previous studies have methodological weaknesses and unanswered questions. For example, studies in the crowding field generally do not address EDA collection and evaluation. This is a very complex subject area with a specific set of problems related to experimental conditions, artifact consideration, and interpretation; Chapter 3 of this thesis addresses this issue in detail. Furthermore, the discussed studies strongly indicate that the recording of density also requires a clear experimental design. For example, in LaJeunesse’s (2021) study, density is defined only in terms of the characteristics associated with the area. Thus, to date, information on what constitutes real density and violations of personal space is lacking. It is also unclear whether the arousal found in the studies is related to the specified violation.

There is also limited reporting of what happens during the walk, and confounding factors such as loud noise have not been examined. For instance, Engelniederhammer et al. (2019) do not provide information about what happened away from the walk. In their virtual reality study, Mudassar et al. (2021) showed that the influence of crossing a road depended on approaching cars; therefore, road crossing information and details about the conditions would be important for excluding confounding events, but this was not collected. The studies of Mavros et al. (2022) and Zhao et al. (2019), conducted in more controlled environments, excluded the confounding properties of the field. However, the study by Mavros et al. (2022) mainly examined the influence of the environment on the stress experience of crowded situations and only investigate the visual confrontation with density. Therefore, questions about the influence of violations on personal space remain. In pedestrian research, there are two specific conditions— “walking” and “standing”—however, questions about the differences in the perceptions of density for these two conditions have not been answered. Also missing are adjustments to treadmill speeds in laboratory density situations to make the measurements more realistic. Only the study by Zhao (2019), investigated the effect of lateral human-generated constriction. The study did not consider personal space. However, its results indicate that lateral violation of personal space may also be an influencing factor in arousal. Furthermore, a change in velocity enforced by obstacles represents a possible explanation for increased arousal.

2.5 Research Questions

The studies on density and personal space, whether based on EDA or self-reports, indicate how complex the experience and perception of density ultimately are. This research aimed to contribute to developing a more profound understanding of arousal states in density situations and further deepen the previous findings. The controlled use of EDA as an objective method of recording stress experience in density situations was the focus of this work. Supplemented by subjective data collection methods, this methodological approach was used to provide expands the understanding of PLOS.

However, within the framework of previous research, only short-term violations of personal space in the form of people passing other people have generally been studied. Studies on prolonged exposure to dense situations, such as those encountered on trains or while waiting in queues, have not yet been conducted. Similarly, the act of walking in a stream of people and its associated effects on pedestrians have not yet been considered in studies using EDA as an objective indicator of stress. The theories and studies presented in this chapter give a strong indication of the nature of the link between stress and the violation of personal space. This relationship strongly suggests that density has an influence on pedestrians' experience of stress. However, walking speed is also a crucial parameter in the daily lives of pedestrians. In crowded situations other pedestrian often constrain the walking speed. It is questionable whether the restriction of walking speed alone, or the restriction imposed by other people, leads to stress.

Overall, studies on subjective density perceptions show different results due to their context dependence. The results suggest that to achieve a basic understanding of the relationship, non-controllable, confounding influencing factors like street noise should be omitted as much as possible. Therefore, I conducted experiments without cover stories and hidden targets. Of course, a completely context-free setting is not possible, but the subjects were not instructed how to behave or to which situation in everyday life it is comparable. In addition, the influence of externally reduced walking speeds was considered free of the density parameter to investigate whether stress is triggered by not being able to walk at a pleasant speed. Finally, the impact of the PLOS-derived relationship between density and speed on stress levels was considered.

To this end, four reductive and exploratory experiments were conducted to gain an understanding of the perception of being in different density levels over extended periods of time. The studies answered the following questions (RQs):

Studies 1 and 2:

- RQ1. What effects does waiting in different density levels, measured by people per m^2, have on subjective and objective stress parameters?
- RQ2. Is communication a coping mechanism for dealing with waiting in high density?

Study 3:

- RQ3. What are the effects of different externally restricted walking speeds and freely chosen walking speeds on subjects' stress scores?

Study 4:

- RQ4. What effects do density and the associated reduced walking speeds have on the stress scores of walking subjects?

3 Methodological Considerations for Collecting EDA Data

Guidelines have been established by Boucsein et al. (2012) for EDA data collected in the laboratory. The American Psychological Association (APA) recognized them as recommendations and they contain statements about preprocessing and artifact handling. During the last few years, the focus of the crowding research field has increasingly shifted to data collection in the field. However, these data place different demands on preprocessing and artifact handling than do laboratory data. Therefore, the following chapter presents the methodological peculiarities of the EDA method. Within this framework, I also describe different possible preprocessing steps for the raw EDA data and the advantages and disadvantages of each step. At the end of the chapter, the preprocessing steps and parameters used for the analysis of the EDA data collected in this research are explained.

3.1 Basics of EDA Measurement

As mentioned in Chapter 2, EDA is a method to measure the physiological response of the sympathetic nervous system. Another name for EDA is also galvanic skin response. The unit in which skin conductance (SC) is measured in microsiemens (µS) (Boucsein, 2012). It should be noted that SC is a highly individual measure, so the range of measured values is between 2 and 30 µS (Gramann & Schandry, 2009). The EDA signal is a complex signal, which include phasic and tonic components. The distinction of these components is easy. Figure 2 shows the EDA curve for one person. Essentially, the EDA curve consists of a slowly changing tonic baseline and a fast phasic response.

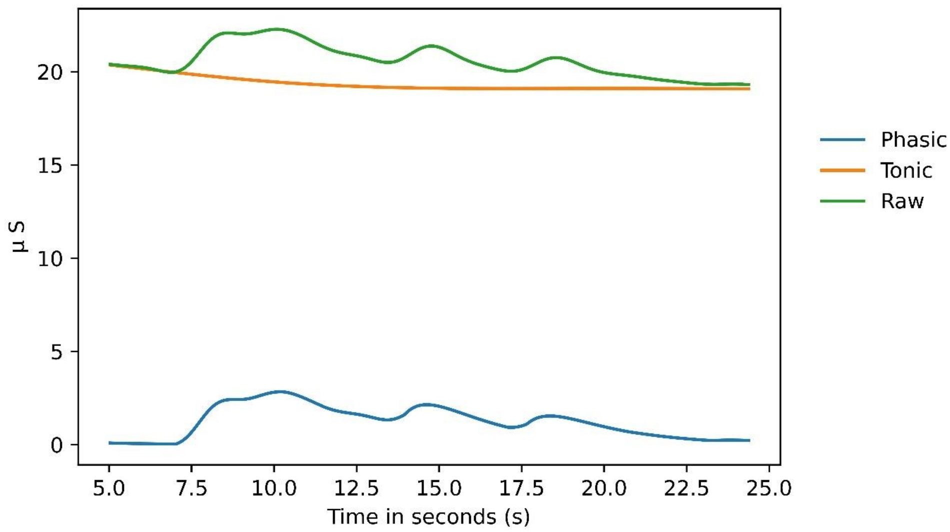


Figure 2: The two EDA components (tonic and phasic) and the raw EDA signal for one person.

When analyzing EDA signals, a distinction is made between event-oriented analyses and interval-oriented analyses. Event-oriented analyses require information about the temporal occurrence of a stimulus, as in the studies of Engelniederhammer et al. (2019) and Zhao et al. (2019). In the absence of this information, interval-oriented analyses can be used, especially when conditions are constant across the time interval, as in studies by LaJeunesse et al. (2021) and Mavros et al. (2022). In the following subsections, I discuss the phasic parameters used in event-oriented analyses and the tonic parameters used in interval-oriented analyses.

3.1.1 Phasic parameters

The phasic parameter is based on the phasic component of the EDA signal and is called the skin conductance response (SCR) (Boucsein, 2012). This parameter is used in event-oriented analyses and the direct response to a stimulus/event is measured (van Halem et al., 2020). Different collected sub-parameters achieve a good estimation of the response to a stimulus; the sub-parameters include the latency until the onset of the SCR, the rise time of the SCR (onset to peak), the amplitude, and the half-life of a rise. The assignment of a peak to a stimulus is accomplished using the average duration until the onset of a response. This is between 1 and 5 seconds (Berntson et al., 2017; Boucsein, 1988; Cacioppo et al., 2012; Dawson et al., 2017). Between the stimulus presentation and complete decay of a peak lies up to 10 seconds (Boucsein, 2012). Furthermore, peaks do not occur individually; they can also overlap. This is called a type 2 SCR. In this case, a renewed rapid increase in skin conductivity occurs before the peak has completely subsided. One reason this increase can occur is because the test subject thought of something unpleasant. However, type 2 SCRs can also be an artifact (Gashi et al., 2020); artifacts are discussed in detail later in this thesis. Overall, the EDA is a slow method for measuring response to stimuli. The minimum amplitude for an SCR varies in the literature from 0.01 (Braithwaite et al., 2013) to .05 or even .1 µS (Boucsein, 2012; Dawson et al., 2017; Gashi et al., 2020).

3.1.2 Tonic parameter

As mentioned above, emotional or startle events are not the only events that lead to the reaction of the phasic component; spontaneous fluctuations also occur. These spontaneous fluctuations, together with responses to unidentified events, are referred to as the nonspecific skin conductance response (NS.SCR) and are used as tonic parameters in interval-based analyses (Boucsein, 2012). In general, spontaneous fluctuations range from 3 to 7 peaks per minute (Boucsein, 2012); when these values are exceeded, an elevated stress level can be assumed. Thus, the number of NS.SCR events can be used as an indicator of stress (Kleckner et al., 2021). Therefore, it is worth calculating the averaged amplitude over the whole interval to make a statement about the stress intensity.

Unlike the phasic component, the tonic component changes only slowly. Furthermore, variation between individuals can be found. From the tonic component, the skin conductance level (SCL) parameter is calculated over the mean value of the interval (Posada-Quintero & Chon, 2020; Topoglu et al., 2020). In addition to calculating the mean value for the entire interval, when considering time intervals, it may also be useful to examine the course of different experimental conditions averaged over all subjects to identify peculiarities and similarities that may be due to the experimental design or procedure.

3.1.3 Extended EDA parameters

In addition to the indicators that are classically listed as parameters in the literature, Posada-Quintero et al. (2016) developed another parameter that is based on the power spectral density analysis of the heart rate and is frequency-dependent. When measuring the heart rate, spectral analysis evaluates the dynamics of the autonomic nervous system. Two frequency ranges are distinguished, the high-frequency range (0.15 to 0.4 Hz), which is associated with the parasympathetic nervous system, and the low-frequency range (0.045 to 0.15 Hz), which is associated with the sympathetic nervous system. Since the sympathetic nervous system innervates EDA, only the low-frequency range is relevant. The parameter is called EDA Symp and the selected frequency range is between 0.045 and 0.25 Hz, according to Posada-Quintero et al.

(2016) and Ghiasi et al. (2018). The parameter has been validated in typical laboratory experiments about stress in psychology (Stroop, cold pressure, 70° head-up tilt test). As a controlling variable of the sympathetic nervous system, the studies also collected the heart rate. The parameter has been used in exercise studies. In this context, Posada-Quintero et al. (2018) investigated the usefulness of the parameter in measuring sympathetic activity at different exercise intensities on a treadmill. They showed that during vigorous exercise, the frequency limit was about 0.37 Hz. Due to the potential for the differentiation of physiological activity and the frequency range associated with stress, the EDA Symp can be an interesting complementary measure, in which physical activity does not contaminated the results like the classical SCL and NS.SCR parameters.

3.2 Data Quality

When collecting physiological parameters, data quality is crucial for the validity of the results. Thus, artifacts lead to distorted data, which can overlay the stimuli-situation relationship and thus lead to misinterpretations. The following subsections discuss artifact detection and correction.

3.2.1 Artifact detection

The quality of the data analysis is dependent on the quality of the data itself. Since physiological data are usually not free of artifacts even in the laboratory under controlled conditions, the conditions must incorporate an estimate of data quality. When using mobile EDA measurement devices, new types of artifacts occur in addition to well-known artifacts, such as lost electrode contact or electrical noise due to the applied voltage. In addition, field studies do not have constant conditions, in contrast to laboratory studies and, for example, temperature and humidity can falsify the results (Gashi et al., 2020). The biggest problem, however, arises because of motion artifacts. Since the subjects are supposed to move freely in field experiments, the natural conscious or unconscious movement of the body (for example, the hands), should not be restricted. This means that the dataset must be cleaned regarding possible artifacts. Manual tagging of artifacts is highly tedious and time-consuming, therefore, there has been considerable interest in automatically controlled artifact detection in studies using EDA measurements. Several approaches to automatic artifact detection have been recently developed (Chen et al., 2015; Gashi et al., 2020; Kelsey, 2017; Subramanian et al., 2022; Taylor et al., 2015). These approaches use observed or unobserved machine learning algorithms, and support vector machine (Taylor et al., 2015), wavelet transform (W. Chen et al., 2015), and batch orthogonal matching pursuit methods (Kelsey, 2017), among others. However, most approaches have been tested on data collected in the laboratory. As mentioned above, the artifacts of stationary seated laboratory-collected data are significantly different from the artifacts found in the data from field investigations. Stationary seated experiments tend to be conducted in the laboratory while motion experiments tend to be conducted in the field. However, both stationary seated and motion experiments can be conducted in laboratory settings (Mavros et al., 2022; Posada-Quintero et al., 2018). Laboratory experiments with motion are also performed in the context of this research. Therefore, approaches to artifact detection in the field are considered here to shed light on the handling of motion artifacts.

An approach to dealing with data collected in the field is presented by Gashi et al. (2020). This approach uses neural networks and ensemble classifiers to distinguish two different types of artifacts. The first is shape artifacts, where the signal differs significantly from the physiological response, such as an abrupt rise or fall of the graph. The second is the influence of motion and temperature artifacts, in which increased physical effort due to changing conditions cause the physiological response. These artifacts are not different in signal shape from physiological responses, so to detect such artifacts, using information from sub-sensors integrated into the EDA sensor is helpful. An accelerometer integrated into the sensor collects the change in motion, while a thermometer collects the temperature differences. The algorithm was written for data from the Empirica4 sensor and is publicly available (GitHub, 2023c) but it cannot be readily applied to the sensor used in this work.

Unlike the approaches that use neural networks and deep learning algorithms to detect artifacts, Kleckner et al. (2018) present a rule-based approach. In this approach, four rules automatically check the data for artifacts:

1. The data are in the range from 0.05 µS to 60 µS.
2. The data change too fast (+10 µS/s).
3. The temperature is not between 30° and 40°C.
4. Data (e.g., over an interval of 5 seconds) surrounding a segment identified as erroneous according to Rules 1 to 3 are also considered erroneous.

The rules were established as part of a long-term study in a domestic context and were adapted to the context. For example, Rule 3 checked whether the sensor was worn or not. If the temperature was outside this range, the probability that the sensor on the body was not worn was very high. This approach showed high agreement with the algorithm-based approach of Taylor et al.’s (2015) human observation-based artifact detection. For a while, the algorithm was available as an online tool and can still be found in the Matlab tool Biosignal/Specific Procession (Nouhi, 2023).

Gashi et al. (2020) published six rules for the manual detection of artifacts in motion, which were based on an extensive literature review. They trained the above-mentioned automatic algorithm using manually inspected training sets based on these rules. In doing so, they achieved good results. These rules, unlike Kleckner et al.'s (2018), distinguished between the tonic signal or mixed signal and the phasic signal. As a result, the rules are somewhat more discriminating:

1. EDA is outside the value range (0.01 to 100 µS).
2. Abrupt increase in EDA (no SCR is present and the signal increases by more than 0.1 µS/s).
3. An abrupt drop in EDA (no SCR is present and EDA drops by more than 0.1 µS/s).
4. SCR drops too fast (sudden drop of SCR by 0.1 µS and a half-life of less than 2 seconds).
5. The SCR increases too fast (more than 1 µS/ s).
6. The frequency of SCRs is too high. This means that there are three consecutive SCRs in a segment of 5 seconds, and thus there is a high overlap of SCRs.

In the research presented here, these six rules were implemented in Python, and visual inspection was used to support them. In addition, rapid changes in activity level, measured by the accelerometer in the EDA sensor, were included. To calculate the activity level, the three axes (x, y, z) of the accelerometer were included using the following formula (Gashi et al., 2020):

$$\text{activity level} = \sqrt{x^2 + y^2 + x^2}$$

Subsequently, the merged value was plotted and changes in the activity level, such as a sudden steep increase, could be quickly detected.

In this research, the analysis of all the experimental data using Gashi et al.'s (2020) rules showed that the data collected in the stationary (waiting) experiments often violated Rules 2 and 3. This suggests that not only motion artifacts violate these rules, also the normal course of the EDA data collection already violate the rules. A possible reason for this could have been the used sensors. To minimize the influence of possibly unrecognized SCRs, the analysis was also performed with the tonic component. Here too, a similar value of violation of rules 2 and 3 show up in stationary and moition studies (Table 1).

Table 1: Mean percentage of the violations against rule 2 and 3 of Gashi et al. (2020) compared for the walking and waiting studies conducted in the thesis.

Study	Rule 2	Rule 3
Walking study	5.74 %	5.98 %
Waiting study	3.84 %	3.67 %

Because of the frequent violations of rules 2 and 3 while standing these rules were adjusted. The adaptations were based on Kleckner et al. (2018) and Gashi et al. (2020) and the requirements of the preprocessing used in this work. The following rules support the visual inspection:

1. EDA is outside the range of values from 0.9 to 100 µS.
2. There is a sudden change in the tonic component (either an abrupt increase or decrease in the tonic component) when no SCR is present and the signal decreases by more than 1 µS/s.
3. The SCR drops too rapidly (a sudden drop in SCR of 0.5 µS occurs and the half-life is less than 2 seconds).
4. SCR increases too rapidly (more than 1 µS/s).

The whole process shows that there is not a universally valid solution for detecting artifacts automatically, and it is important to check the data visually. The physical activity was plotted alongside the EDA data, making it easy to recognize sudden changes and directly inspect the EDA data (Figure 3).

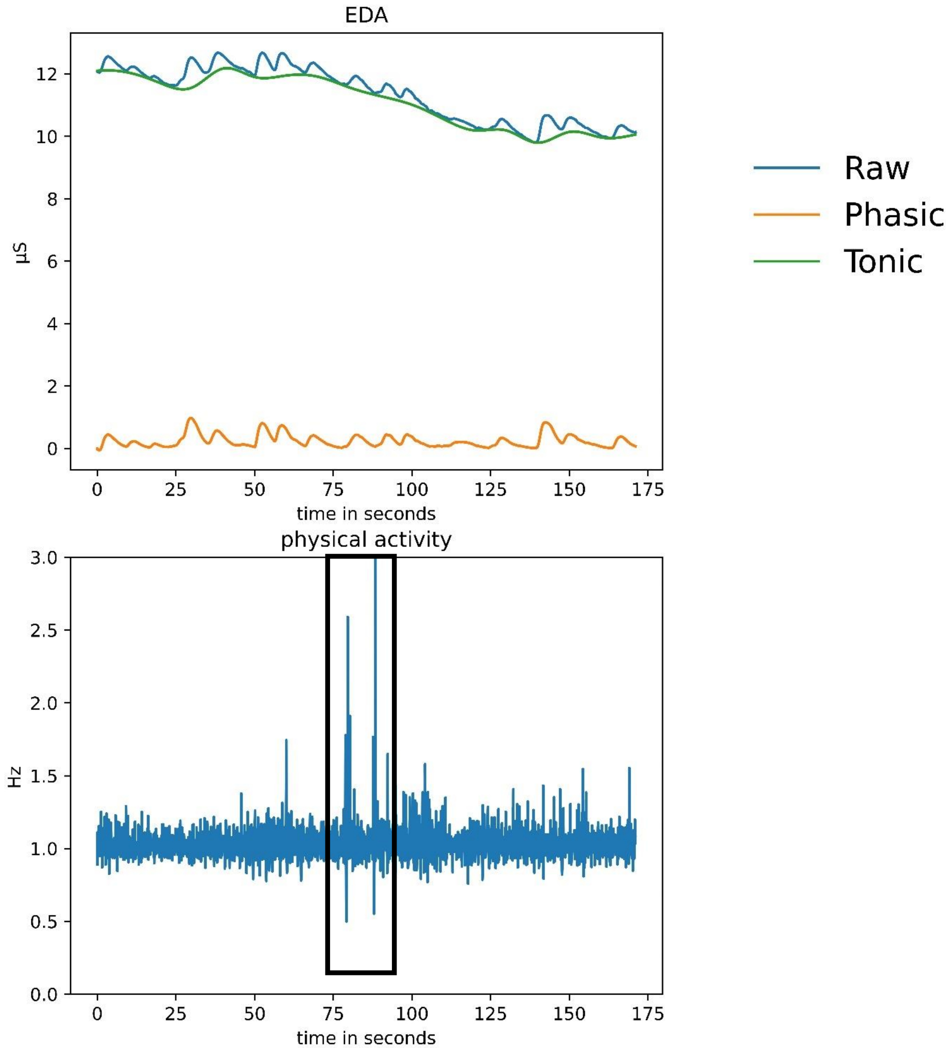


Figure 3: An example of the presentation of the artifact detection with plot of EDA and physical activity. The black box marks sudden change in physical activity.

After the artifacts have been recognized, the question arises of how to deal with recognized artifacts in a methodologically meaningful way.

3.2.2 Artifact correction

The classic methods of artifact correction include filtering. Filtering uses a Butterworth low-pass filter with a cutoff frequency of 1 Hz to remove erroneous frequencies (Topoglu et al., 2020). These methods find use in Python packages (Neurokit) (Makowski et al., 2021) and Biosppy (GitHub, 2023a). However, they can lead to the masking of physiological responses. They are also not as well suited for the higher amplitude artifacts that are more common in natural settings, such as field experiments (Topoglu et al., 2020). Other methods include interpolating erroneous data through a spline (GitHub, 2022) or exponential smoothing (GitHub, 2023a). Linear interpolation is also cited as a method by Subramanian et al. (2022). However, any interpolation of data must consider that the original information is lost. The interpolation of a few seconds does not cause a problem, but the correction of longer periods does.

In this work, the rule-based algorithm support the visual inspection. Due to the short duration of each experimental run and the controlled collection method in the quasi-field experiment, artifact correction was not applied, and the data with too many artifacts were excluded from the analysis.

3.3 Calculation of Characteristic Values

The following sections present various options for data analysis and the preprocessing of EDA data. Common algorithms or practices for determining the above-mentioned EDA parameters are also explained, and the selection for the studies described in Chapter 4 and 5 is justified.

3.3.1 Methods for separating the EDA signal

As mentioned above, EDA consists of different components. The separation of the different signal components and the determination of the SCRs and SCL are interesting topics in the scientific community and the following paragraphs discussed the different methods. In support of the research presented here, the different methods (see Figure 4) are briefly explained, and a justification is provided for which ones were used for further analysis.

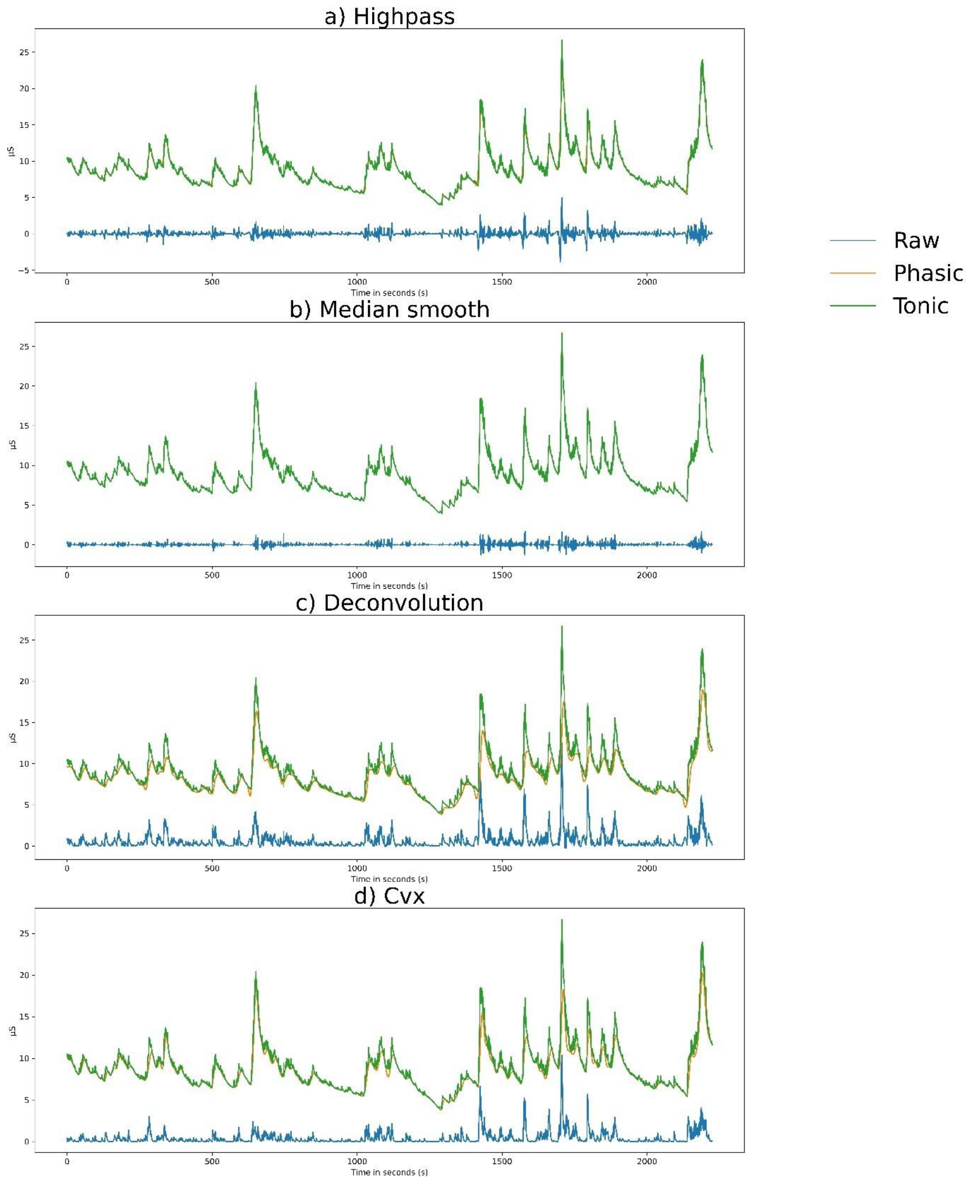


Figure 4: The different methods for separating the tonic and phasic components of EDA.

There are different types of approaches for separating EDA components. On the one hand, well-known companies that sell the sensors, such as Biopac (BIOPAC Systems, Inc., 2023) and Movisens (movisens GmbH, 2023), offer simple approaches to signal separation in the tools they provide. Biopac offers two methods of separation. In the first, to obtain the tonic component the median smooth the SC signal. Then the difference between the raw data and the tonic component gives the phasic component. As an alternative method, Biopac offers separation using filters. Here, the signal for the phasic component is clipped with a Butterworth high-pass filter at a cutout frequency of 0.05 Hz (Braithwaite et al., 2013). On the other hand, for the tonic component, the data is filtered with a Butterworth low-pass filter and a cutout frequency of 0.05 Hz (Topoglu et al., 2020). Movisens, on the other hand, offers a low-pass filter with a frequency of 0.1 Hz to obtain the tonic component (*Movisens Docs*, 2023). The use of filters assumes that different components are systematically associated with different frequencies.

In comparison, various research groups use far more complex mathematical models to achieve more precise analyses of the components. In the following, I will briefly discuss the two best-known approaches based on mathematical models. For a more detailed overview, the review by Posada-Quintero and Chon (2020) is recommended.

One of the best-known approaches is that of Benedek and Kaernbach (2010a). They used non-negative deconvolution to separate the EDA components (Benedek & Kaernbach, 2010b). In this approach, the phasic and tonic signals are separated using their impulse response, and the tonic and phasic activity are derived from this. The researchers changed their approach to continuous decomposition; overall, this optimization simplified the evaluation of the phasic activity and is less computationally intensive, but at the same time, it slows the analyses and is less robust to artifacts (Kelsey, 2017). This approach is freely available in the Matlab tool Ledalab and the Python tool Ledapy (GitHub, 2022).

Another widely used approach is the convex approximation approach (cvxEDA) by Grecco and colleagues (2016). Here, the EDA signal is understood as a combination of the tonic and phasic signals and noise. The noise includes, among other things, measurement errors, errors in the model, or artifacts, and a white Gaussian noise term represents it. The assumption is that the phasic component is a combination of the infinite impulse function and a non-negative and sparse driver of the sudomotor nerve. Therefore, the algorithm uses an autoregressive moving average (ARMA) model and maximum à posteriori (MAP) estimation and convex approximation method. The two selectable parameters (alpha and gamma) allow consideration of inter- but also intra-individual variations (see Figure 5) (Topoglu et al., 2020). A low computational cost characterized the model, and it is robust against noise.

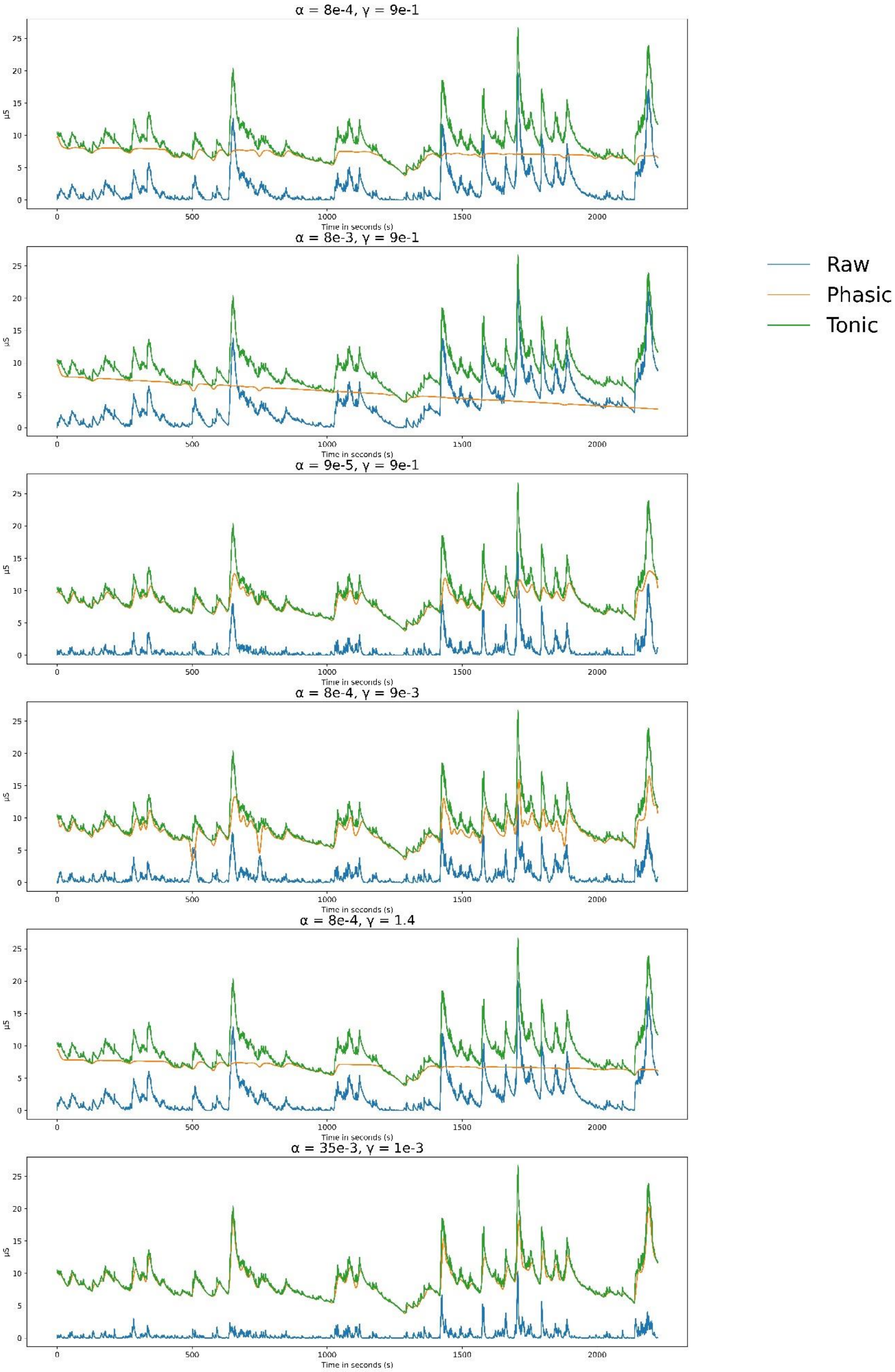


Figure 5: Representation of the influence of different values of α and γ in the cvxEDA approach.

A study by Kelsey (2017) showed better discrimination of the cvxEDA approach (Grecco et al, 2016) compared to the Benedek and Kaernbach (2010a, 2010b) approach, which does not require knowledge about the presented stimuli. The authors provide both a Matlab (Citi, 2023) and Python script (GitHub, 2023b).

As seen in Figure 4, separation of the signal using simple methods (median smoothing and high pass) often results in a negative value of the phasic component. Since the sweat glands secrete either more or less fluid but can never remove fluid from the environment, there is physiologically no negative response from the EDA (Posada-Quintero & Chon, 2020) and therefore these methods of using separation were omitted for this work. Overall, as mentioned above, the cvxEDA approach of Greco et al. (2016) shows better fitting results than the Benedek and Kaernbach (2010a, 2010b) method (Kelsey et al., 2018). Moreover, by adjusting alpha and gamma, the cvxEDA approach has the advantage of adapting intra- and individual differences and obtaining better results. Due to these advantages, the algorithm chosen for this work was Grecco et al.'s (2016) cvxEDA approach.

3.3.2 Standardization of data

As mentioned earlier, EDA data have interindividual differences in the values by which the readings vary. For example, one person's values may be around 2 µS and another person's values may be around 30 µS (Boucsein, 2012). These differences pose problems for subject comparability, especially when using the mean SCL. One way to ensure the comparability of different test conditions in experiments is to require all subjects to undergo all conditions. However, this is often not feasible, either due to habituation effects when repeatedly running the different experimental conditions or time-economic reasons. However, to ensure comparisons between different groups, a statistical method called standardization is necessary. A not-so-common possibility is the minimum-maximum standardization (Dawson, 2007; Dawson et al., 2007). Here, the formula

$$z_j = \frac{x_j - \min(x_{baseline})}{\max(x_{baseline}) - \min(x_{baseline})}$$

is applied. A basic requirement for this method is the collection of a baseline. A recommended method in the statistics literature is z-standardization (Ben-Shakhar, 1985; Taylor et al., 2015).

$$z_j = \frac{x_j - \mu}{\sigma}$$

µ: Mean σ: Standard deviation

Here, the mean and standard deviation compressed the data. What is not clear in the literature is what data basis should generate the mean and standard deviation. Thus, there are three different databases:

- Total dataset
- Baseline
- Any experimental condition

Each of the methods has advantages and disadvantages. The biggest problem with the choice of data baseline is that effects are no longer present or are overestimated due to compression with the wrong parameters. The study design should decide about which method of standardization fits best. For example, in studies involving movement or tasks, it is often useful to start at a baseline in which the subjects are standing or sitting quietly (Posada-Quintero et al., 2018). Meanwhile, for the standardization of experiments at rest, experimental conditions with low distraction can also be used.

3.3.3 The SCL Algorithm

Standardization of the data is especially important for the parameters of the tonic component. Therefore, depending on the study design, calculating SCL values uses either previously standardized values (if two different groups of subjects are compared) or the original values (if conditions that all subjects are in are compared). The SCL parameter (SCL) is the averaged tonic component over the entire experimental period of a condition for each subject. In addition, the changes over time in the experiments are considered. For this, the values of the tonic signal at each time point are averaged over all subjects to obtain an averaged graph (Figure 6).

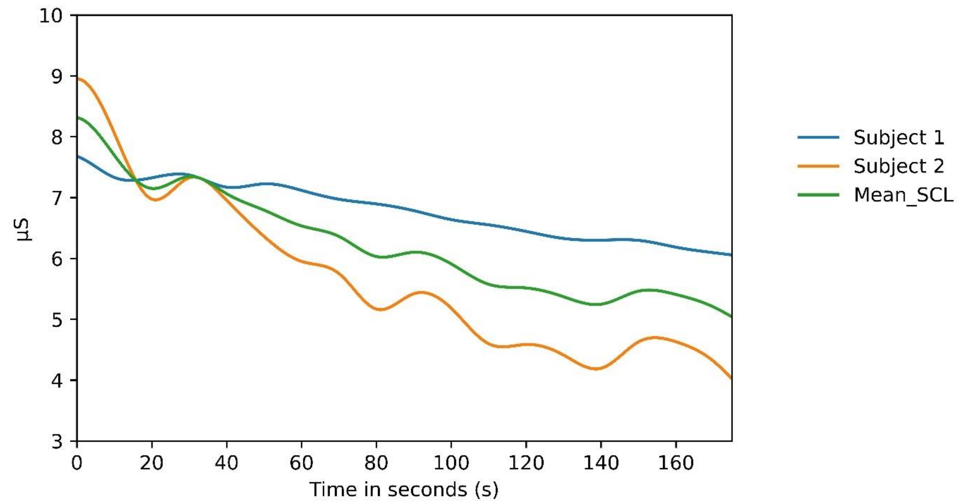


Figure 6: The mean (green) for each time point from two subjects (blue and yellow).

3.3.4 Determination of SCRs

In addition to the differences in the algorithms for separating the individual components, there are also different approaches to determining SCRs. In the past, the determination of peaks was manual work and took a long time (Topoglu et al., 2020). Over time, several research groups have developed approaches to detect SCRs using computer algorithms. For example, Kim et al. (2004) and Nabian et al. (2018) consider the median smoothed phasic signal to determine the crossing of the zero line onset of an SCR. It should be clarified that Kim et al. (2004) use only the initial crossing of the zero line, while Nabian et al. (2018) count the SCRs using differentiation and subsequent convolution with a 20-point Bartlett window. The intersections with the zero line present in the window are considered. Crossing the zero line into the positive region corresponds to the start of the SCR, and crossing the zero line into the negative region corresponds to the end of the SCR. In this case, the maximum between the two marked points defines the amplitude. These approaches were not considered in this work because the method of separation should not lead to a phasic signal crossing the zero line because, as already described above, physiologically a negative reaction is not possible.

In addition to the methods already mentioned, rule-based algorithms can also be used, for example, Movisens Docs (2023) uses the criteria of Dawson et al. (2007) and Boucsein et al. (2012) to determine SCRs According to this approach, peaks are detected if the phasic component rises by at least 0.05 µS/s and the graph rises for at least 0.9 seconds before falling again. In addition, the amplitude must be at least 0.1 µS. Furthermore, in the Python package Neurokit (Makowski et al., 2021) and the EDA-explorer approach of Taylor et al. (2015), local maxima are determined by nearest neighbor comparisons; if these meet the requirements, they are counted as SCRs. For interval-based analyses, as mentioned above, the parameter (NS.SCR) is the number of SCRs in the interval.

For the detection of SCRs, the amplitudes of the response are crucial. The choice of amplitude for an SCR is not uniform. For example, a minimum amplitude of 0.1 µS is often required in the literature (Dawson et al., 2017). However, there are also studies where the minimum amplitude is between 0.01 µS and 0.05 µS (Braithwaite et al., 2013). In this research, due to the exploratory nature of the experiments, the limit was set to a minimum amplitude of 0.01 µS for the peaks.

3.3.5 Algorithm for determining the parameter EDA Symp

EDA Symp is a new parameter, which based on a short-time Fourier transformation. The data were down-sampled to a sampling frequency of 2 Hz. Then a lowcut Butterworth of order 8 filtered the data. The data overlap was chosen to be 50 according to Posada-Quintero et al. (2016). Subsequently, a power spectral density analysis according to Welch is performed. The areas under the curve (ROC or AUC) in the relevant range of [0.045 – 0.25 Hz] obtained comparable values. The algorithm used was based on the implementation of the Python package Neurokit2 (Makowski et al., 2021).

3.4 Preprocessing the Data Collected in the Experiments

This section provides information about the sensors, data cropping, and preprocessing steps of this research.

The data was collected using Movisens ambulatory system (movisens GmbH, 2023), specifically the EDA Move 4. The electrodes were placed on the palm of the non-dominant hand of the subjects (Figure 7). Two electrodes with solid gel were used. The sensor collected the raw signal at a sample rate of 32 Hz and measured in µS.

Figure 7: Attaching the EDA electrodes to the palm of a subject's non-dominant hand.

Electrodermal activity data are time-series data that they record continuously, even during experimental pauses. Thus, the raw data cannot be assigned to the different experimental conditions based on visual inspection alone (see Figure 8). To enable a precise assignment of the data to the individual experimental conditions, the experiments are either filmed with a time-code-equipped camera or classified by markers set by the experimenter via a Movisens sensor. In addition, by examining the changes in acceleration data collected by the accelerometer integrated into the EDA Move 4, changes in experimental conditions can be determined. From this information, timetables are determined for individual subjects and experiments. These timetables, via a self-written script, allow the data to be automatically cropped and avoids manual inaccuracies and technical problems with the Unisens viewer, which has proven to be very unstable when cropping the data.

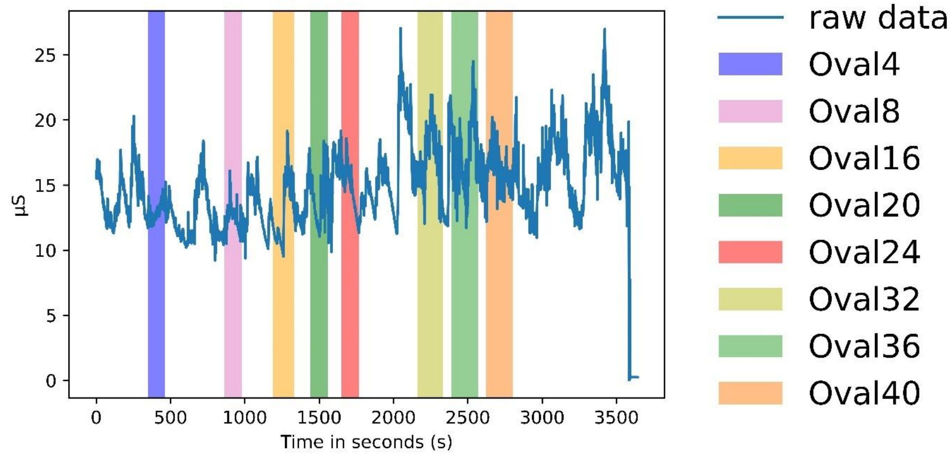


Figure 8: An example of the EDA signal for one subject during the entire experimental period of Study 4.

Python (version 3.7) processed the raw data. A first-order Butterworth low-pass filter with a cut-off frequency of 0.6 Hz cleaned the data from electrical noise. Because of this preprocessing procedure, all subjects with values below 0.9 µS were excluded from further analysis. An algorithm-assisted visual inspection of the data as described above followed. For further analysis, the data were separated into tonic and phasic components. The separation of the data was done using the cvxEDA approach of Greco et al. (2016). The experimental conditions were separated independently. Using the nearest neighbor comparisons of Neurokit, the peaks (NS.SCR) that had an amplitude greater than 0.01 µS were marked and then counted for each individual experimental condition. The mean value of the tonic component calculated the SCL parameter. For the parameter EDA Symp, the raw data were processed analogously following Posada-Quintero et al. (2016).

4 Empirical Framework

The following chapters present the exploratory studies and describe that address the research questions related to how individuals experience density. First, the overall project in which the research questions are embedded is briefly presented. The experimental designs and the operationalization of the experimental condition "density" are then explained. After this chapter the presentation of the studies in Chapter 5 and 6 follows. These chapters are presented analogously to previously published methodological papers and include methodology, results, and discussion subsections.

The variation of the experimental condition "density" was theory-based, as was the differentiation regarding the behavior of the test subjects in two conditions: "waiting" and "walking.". In this thesis waiting only includes standing people.

4.1 The CroMa Project

The experiments presented in this chapter were conducted as part of the "CroMa—Crowd Management in Transport Infrastructures" Project, which was funded by the German Federal Ministry of Education and Research (BMBF) as part of the "Research for Civil Security" program (Funding Codes: 13N14530 to 13N14533). The project began in August 2018 and ended in July 2022. Due to the onset of the COVID-19 pandemic in 2020, the first large-scale experiments planned for the project were canceled due to the ban on gatherings of large crowds. As a result, the project duration was extended by one year, so that the experiments could still be carried out, albeit with a deviation from the original planning schedule.

The project was a larger collaborative project that examined a range of different issues. The project partners were:

- University of Wuppertal:
    - Chair of Computer Simulations for Fire Protection and Pedestrian Traffic
    - Department of Civil Protection, Disaster Relief and Property Security
- Research centrum Jülich GmbH: Institute IAS-7: Civil Safety Research
- Ruhr-Universität Bochum: Chair of Social Theory and Social Psychology
- Düsseldorf Congress GmbH (2018-2020)
- D.LIVE (since 2020)

Participating in the project as associated partners, subcontractors and implementation partners were:

- Swiss Federal Railways AG: Infrastructure, Installations and Technology Division
- Cologne Public Transport Company AG
- DB Analytics: Mobility Departments (ES.VM): Simulation, Data Traffic Forecast (ES.VS)
- Federal Police: Federal Police Inspectorate Düsseldorf
- eps GmbH
- Special Security Services Germany GmbH
- German Railways AG
- City of Düsseldorf: Department of Fire, Rescue and Civil Protection
- Association of German Transport Companies
- Rheinbahn AG

The CroMa Project aimed to analyze conditions for the increased robustness of transport infrastructures against peak loads. The high importance of this approach has since become clear, for example, because of the overcrowding of railroads, platforms, and access points due to the temporary introduction of the 9-Euro-Ticket, but also the increase in everyday commuter traffic due to the energy transition. The overall project included three focus packages:

- Structural measures
- Crowd management
- Inter-organizational communication

In addition to the development of an action guide on the topic of “A working aid for the implementation of structural measures and inter-organizational cooperation for crowd management at train stations” (Beermann et al., 2022), the focus of the CroMa Project was on the development and testing of new methods and measurement procedures for scientific analyses. The aim was to gain a better understanding of the behavior and experience of people on train platforms or even in crowds. As described in the theory section of this thesis, previous studies on this topic have generally failed to map the experiences of people based on objective parameters. In addition, a new LOS for travel platforms was developed, in which different aspects of concrete use and how they affect people during their stay were examined in addition to the overall platform itself. For example, the waiting area was evaluated as a function of the expected waiting time for boarders in the short and long terms. Furthermore, the passenger exchanges, the danger areas at the edge of the platform, and the walking paths of disembarking ferry passengers were also evaluated. This classification defined the different states—waiting, moving, or walking—in which pedestrians can be found in transport systems.

In order to gather the empirical basis for the LOS on travel platforms, various experiments were conducted as part of the project to gain a better understanding of people waiting and moving in crowds. This included using EDA to measure arousal to investigate the experience of people waiting and walking in high densities. The exploratory studies described below took place either at the Ruhr-Universität Bochum or as part of the large-scale experiments in the CroMa Project. The large-scale experiments took place in October 2021 and lasted for four days with a total of 1038 subjects and seven experimental setups; for more detailed information see Boomers et al. (2023).

4.2 Experimental Designs

As stated in Chapter 2, pedestrian density is a central issue in pedestrian traffic research. Furthermore, existing studies show that pedestrians, as a part of the traffic system, form different experience states depending on whether they are walking on their way to a destination or stationary while waiting. This research is consistent with Fruin (1987), who also considered the two states of people in traffic systems separately; thus, he developed a PLOS for walking and one for waiting (Holl, 2016).

The objective of this chapter is to present the studies conducted to investigate the effects of density and its interaction with the different states (moving or waiting) of pedestrians in transportation infrastructures. Related to this, the impact of personal space violations on individuals was also investigated to gain a better understanding of the experience of density based on both subjectively and objectively measured stress data. To this end, four exploratory studies are presented below. The studies consider two parameters—density and velocity—separately, as well as the relationship between them. The subjects behave analogously to the conditions found in traffic facilities, that is, “walking” and “stationary standing”; the latter is referred to as “waiting” in the following sections. When walking is combined with density, there is an automatic reduction in speed, as is experienced in crowds. Table 2 shows the assignment of the individual conditions and parameters to the different studies.

Table 2: Presentation of the parameters and conditions used in the different studies.

		Parameter	
		Density	Walking speed
Experimental condition	Waiting	Studies 1 and 2	
	Walking	Study 4	Study 3

There was no experimental study for waiting and the parameter speed because when people are standing, they have a speed of zero. While the influence of the speed of passing persons could be considered, this was not the focus of the research.

4.2.1 Research design: Studies on Waiting

For the waiting experiments (Studies 1 and 2), the stay in different densities was considered. More precisely, the experiments focused on the influence of the change in social density. For this purpose, a standardized area of one square meter (m^2) was filled with more and more people. With increasing density, the space available to the individual becomes smaller and smaller. Thus, the individual space requirement is more and more restricted, and personal space is more and more violated. According to the theories discussed in Chapter 2, it was assumed that violation of personal space leads to higher stress. To increase the external validity, the densities in the two experiments were exposed to different lengths of time to better assess the effect of waiting longer in different densities. The density situations being studied experimentally also varied in length consistent with everyday life situations, such as standing at a train station or standing on a crowded train. From a methodological point of view, investigating waiting in an experimental setting ensures a more controlled observation of the EDA measurement, since problems with motion artifacts caused by walking do not play a role. The exact experimental setups and the specific variations of the conditions are discussed in Chapter 5 and 6, where the individual studies are presented.

4.2.2 Research design: Studies on Walking

4.2.2.1 Speed

The focus on observing the influence of walking speed on excitation level resulted from two aspects. From a methodological point of view, there was the possibility of observing the effect of motion on the EDA signal relative to different constant speeds. Thus, I could gain a better understanding of the possible applications of the EDA signal in the context of studies with defined speeds. In terms of content relevance, the results of Helbing et al.'s (2000) simulation studies suggest that the difference between actual walking speed and desired walking speed leads to discomfort and affects motivation to walk. Both may have implications for the EDA signal. Jia et al. (2022) argue that stress and unpleasant feelings during walking result from the desire to walk at a different speed than is actually possible due to the general conditions.

To investigate these relationships, in this study, the walking speed was set by an experimenter and blocked the subjects' desired speed. The experimenter walked in front of the subject at a constant speed for 3 minutes before smoothly changing to a lower speed. For reasons of experimental economy, but also to maintain the social component, this experiment was performed with several subjects (maximum 5) at the same time. The subjects kept a defined distance of 1.5 m from each other. The individually desired speed was operationalized by allowing the subjects to walk for a distance of 90 m at a freely selected speed. The exact description of the test procedure is given in Section 6.1.2.2.

4.2.2.2 Density

To describe the influence of density on speed, the fundamental diagram is used in pedestrian research. Seyfried et al. (2005) developed a well-known approach for empirically investigating this relationship. In their experimental design, an oval was drawn on the ground and subjects were asked to walk in a line one behind the other along the edge of the oval. More and more subjects were added to the line so that the oval became more and more crowded. As a result, the density increased and the speed decreased. Seyfried et al. (2005) found that the resulting relationship between speed and density from this single-lane movement experiment was consistent with the results of Weidmann (1993). Thus, Seyfried et al. (2005) provided a standardized condition to specifically study the complex relationship between density and velocity as they relate to each other in the fundamental diagram. This means that the influence of external factors such as gender and culture on the relationship can also be examined (Chattaraj et al., 2013; Paetzke et al., 2023). In the work presented here, this approach examined the effect of speed reduced by density and the associated violation of personal space on the experience of physiological arousal.

4.2.3 Operationalization of the concepts of density and personal space

In the density studies, the violation of personal space always played a role in the consideration and classification of the results. As mentioned in Chapter 2, people have different distance zones around them and any intrusion into these distance zones is only perceived as pleasant if that intrusion is by a person (or people) to whom one feels a sense of belonging. If, on the other hand, the person doing the intruding does not belong to an accepted group, this can lead to crowding stress through the violation of personal space. Fruin (1987) also integrated this concept into his PLOSs. However, he assumed that the effect of distance differed between walking and standing persons. This difference was justified by an increased space requirement in the execution of the "walking" task. Table 3 presents the different distance zones according to Hall (1969).

Table 3: Distance zones according to Hall (1966), oriented on Holl et al. (2019).

Distance to the next person in meters	Distance zone	Phase
≥ 7.50	public	far
[3.60; 7.50]		near
[2.20; 3.60]	social	far
[1.20; 2.20]		near
[0.75; 1.20]	personal	far
[0.45; 0.75]		near
[0.15; 0.45]	intimidate	far
≤ 0.15		near

In all the experiments presented in this research, density was operationalized as discussed below.

In the waiting experiments, the effect of the change in social density played an important role. Due to the experimental setup being within a limited space, it was easy to determine the social density, so this was the indicator of density. From the social density calculations, it was possible to determine the space available for each subject. From this value, the distance zone was further determined. To calculate the space available for every subject in each experimental run, an area of 0.1 m^2 for the average body ellipses was determined according to Buchmüller and Weidmann (2006) and multiplied by the number of subjects in the run. The value was then subtracted from the available area of 1 m^2. The number of persons divided the remaining available area, thus obtaining the average available area per person (Table 3). It was noticeable that as soon as the number of persons reached 2, the intimate distance zone was violated. Because of the lack of differentiation between the distance zones and a good physical delineation of the number of persons per m^2, social density was the indicator of the degree of filling for the waiting experiments.

Table 4: Available space for the individuals in each experimental condition and the associated distance zones (Studies 1 and 2).

Number of persons in the tiny 1 m^2 box	Space for each person in m^2	Space for each person after subtracting the area of the human body in meters	Distance zones, taken from Hall (1966)
1	1	0.9	personal far
2	0.50	0.4	intimate far
4	0.25	0.15	intimate near
6	0.167	0.06	intimate near
8	0.125	0.025	intimate near

In contrast, the social or physical density in the experimental setup for the relationship between speed and density was not easy to determine because this was a single-lane experiment and the area to the right and left of the subjects was free. Since by varying the number of people in the oval, only the area in front of and behind the subjects varied, ultimately, the focus was only on the effect of this area. Therefore, in the experiment, the distance to the subject in front was used as an indicator of higher density. For this purpose, the average distance between the subjects was determined using the average body width of 28.1 cm defined by Buchmüller and Weidmann (2006), the distance of the oval, and the number of subjects in the oval. From these measurements, the violations to the different personal space zones could be estimated. Table 18 (Chapter 6.2) lists the available space for each person in each experimental condition and the associated distance zone.

5 Studies on Waiting

This chapter presents Studies 1 and 2 on the effects of density on waiting subjects. Essential parts of the first study have been published in the article Beermann and Sieben (2022). Differences in the values between the published papers and the results presented here reflect the unification of preprocessing the data in the process of working on the thesis. In doing this, however, the message of the data has not changed.

5.1 Density: Study 1

Study 1 used a standardized space—a tiny box of 1 m^2—and systematically compared the effect of different densities on the arousal and comfort of the subjects. The density in the box varied from two to eight persons. The relationship between density and comfort/arousal was examined keeping other potentially influential factors constant. Most of the subjects did not know one other. The context was a neutral experimental setting in a university building. I systematically alternated between "speaking" and "remaining silent" conditions to determine whether explicit communication changed the subjects' behavior and their comfort/discomfort while in the box. Even though I instructed subjects to talk, I did not expect everyone to equally engage in conversation all the time. Especially in the larger groups, I expected some people to talk while others listened. I measured comfort/discomfort both subjectively and objectively: subjectively, by means of questionnaires, and objectively, by measuring EDA. Cameras from above recorded the body positioning of people in the box. In test runs prior to the experiment, I found that up to four people were still able to selectively choose a position in the box. With six or eight people, some people had to involuntarily take an uncomfortable position. Therefore, I assumed that densities greater than four people in a 1 m^2 box are particularly uncomfortable.

5.1.1 Hypotheses

1. In a 1 m^2 box, comfort will decrease with increased density. Higher densities will result in higher NS.SCR, Mean SCR Amplitude, EDA Symp and SCL levels.

2. For a 1 m^2 box, subjects will label densities higher than four people as uncomfortable, as measured through a self-report questionnaire.

3. It is more comfortable to speak while waiting in a 1 m^2 box than to remain silent. Therefore, subjects who "remain silent" will have higher NS.SCR levels and will rate their experience in the box as more negative (as measured through a self-report questionnaire). All subjects will agree with the statement that speaking makes the situation more comfortable.

5.1.2 Materials and methods

5.1.2.1 Subjects

Study 1 was a student study. The subjects were recruited through university lectures, and university Facebook groups and notices. A total of 35 people participated in the study. Due to insufficient EDA signal quality, six subjects were excluded from further analysis. Of the remaining 29 subjects, 14 (48.28%) were female and 12 (41.38%) were male, while three (10.34%) did not specify their gender. The gender distribution was not evenly distributed in the individual conditions because the research did not focus on gender. The average age of the subjects was 22.33 years (+/- 3.55). They each received €5 for participating.

5.1.2.2 Procedure and experimental paradigm

The experiments used an innovative type of experimental design. The authors are not aware of any experiments to date that examined the correlation between arousal and density in an experimental setting. The experimental setup consisted of two boxes, each with a surface area of 1 m^2. The boxes had three fixed sides and one that was movable and functioned as a door. The sides were 150 cm high. The wall height was selected so that the test persons did not “hang out” with their shoulders over the 1 m^2 area (Figure 9). The experiments took place in a corridor at Ruhr University Bochum.

Figure 9: Schematic representation of the Study 1 Tiny Box experimental setup with six subjects per box.

Camera filmed the experiments from above, a ceiling height of over 4 m was used. The EdaMove 4 from Movisens recorded the electrodermal activity, as described in Section 3.4.

Figure 10 shows the experimental procedure. The subjects wear the EDA sensors since shortly after arriving at the experiment site. Subsequently, they answered questionnaires about their demographic information and the frequency they were in crowds or commuted (Phase 1). In Phase 2, the subjects experienced four different levels of density: i.e., two, four, six, and eight people in the 1 m² box. For each, they waited in the box for three minutes. After each waiting phase, the subjects left the box. As mentioned above, no attention was paid to gender distribution when filling the box. Furthermore, two conditions were distinguished inter-individually: speaking and remaining silent. In other words, subjects took part in only the speaking condition or only the remaining silent condition. In both conditions, all four density levels were applied. After the experiment, the subjects were given another questionnaire in which they had to evaluate their experiences in the box (Phase 3).

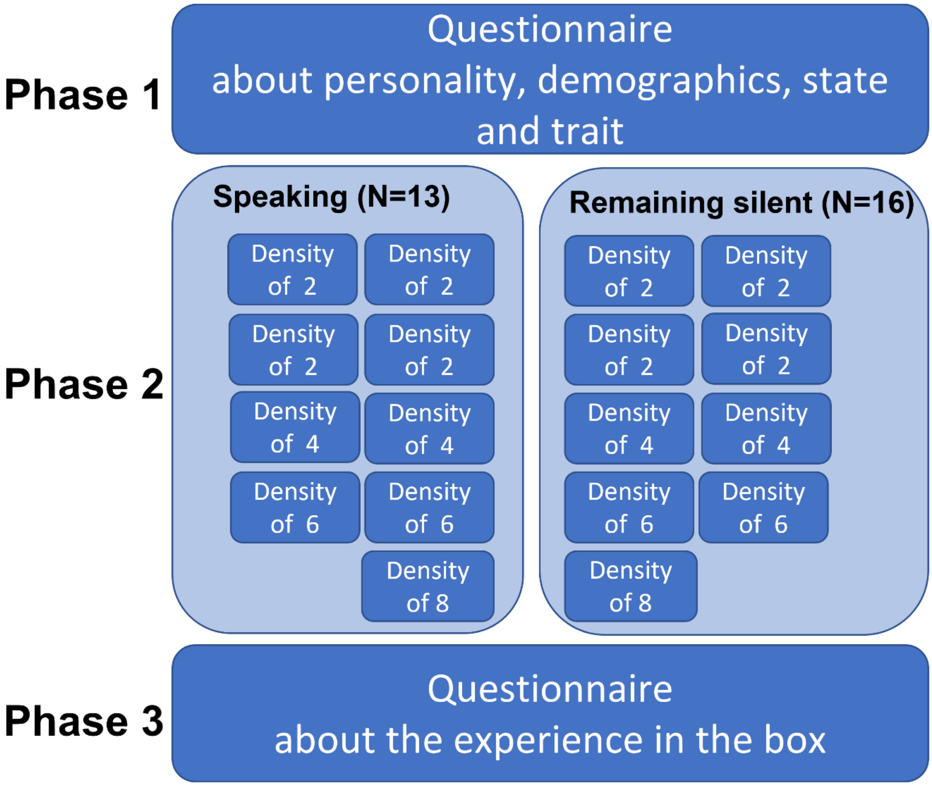


Figure 10: Study 1 experimental procedure. Phases 1 and 3 involved a questionnaire to be completed by all the subjects. Phase 2 shows the split into two conditions (speaking, remaining silent) and the number of density conditions and their loadings.

The Ethics Council of the German Psychological Society (DGPs) approved the experimental procedure.

5.1.2.3 Questionnaire

The Phase 3 questionnaire consisted of eight items. In retrospect, however, I found that not all the items captured the experimental process accurately, therefore I decided to use only four general items in the analysis. All the subjects answered two items: the first ("The physical proximity to other test subjects made me feel uncomfortable.") use a 5-point Likert scale for answer (1 = do not agree at all, 5 = agree strongly); for the second, the subjects indicated the density level that made them feel uncomfortable. Only the subjects in the speaking condition answers the two: using the same 5-point Likert scale, they were asked (1) whether they actively communicated verbally with other subjects and (2) whether communication made the situation more comfortable. Subjects in the silent condition also answered if they would have liked to talk; this was a single-choice question (no/yes) with the option to give an open-ended response if they wished.

5.1.2.4 Statistical analysis

Repeated measures analysis was used to assess the effect of density level on the mean SCL and NS.SCR occurrence. The normality of the SCL and NS.SCR data for each of the four different densities was tested using the Kolmogorov-Smirnov test. When the normal distribution assumption is violated, nonparametric tests are used. However, since the sample contained more than 25 individuals, the violation of the normal distribution assumption was negligible (Wilcox, 1996). Therefore, the parametric repeated-measures one-way analysis of variance (ANOVA) was used to test for significant differences between the density levels. Where the sphericity assumption was violated, the Greenhouse-Geisser correction was used. Subsequently, post-hoc t-tests were used to examine the ANOVA results. The Bonferroni method was used to correct for multiple comparisons. Because of the exploratory design, post-hoc tests were conducted even when the ANOVA was not significant. Chen et al. (2018) recommend conducting both tests in order not to miss any interactions, as the tests differ in their sensitivity and how they analyze the data.

After checking for normal distribution using Levene's test, t-tests were used to analyze the questionnaire data to identify differences between the silent and speaking conditions. The items that were only administered to one condition were used in a descriptive analysis.

5.1.3 Results

5.1.3.1 Results: Questionnaire

The questionnaire findings differed for the speaking and remaining silent conditions. The first item showed no difference between the two groups—in both cases, subjects found the physical proximity in the experiment equally unpleasant. Overall, the subjects most often perceived Density 8 as unpleasant. The mean value for the total sample was 6.857 (SD = 1.671). However, this differed for the two conditions. Thus, subjects in the remaining silent group were more likely to perceive the density as more unpleasant than those in the speaking group ($t_{19.86} = -2.245$, $p = .036$). Looking at the absolute frequency distribution, in the remaining silent group, two subjects considered Density 2 to be unpleasant (M = 6.267, SD = 1.980) while in the speaking condition, subjects indicated only Density 6 and Density 8 as unpleasant (M = 7.538, SD = 0.877). The subjective perceptions also showed that the subjects who were allowed to speak had the impression that speaking made the situation easier (M = 4.538, SD = 0.519). Similarly, most people in the silent condition reported that being able to speak would have made the situation easier (M = 0.643, SD = 0.497).

5.1.3.2 Results: Skin conductance (SC)

From Figure 11, it is very interesting to see that overall, the Density 6 SCL score was initially the lowest; this did not increase until three-quarters of the way through the experiment and then stagnated again. Density 8 began at a medium-high value and, as soon as the pink line representing Density 2 dropped, Density 8 has the highest SCL value over the time period. Therefore, it can be noted that Density 8 leads to the highest long-lasting excitation. There was a significant difference in the SCL means ($F(1.60, 44.77) = 7.129$, $p <= .004$, Greenhouse-Geisser corrected) and a significant difference for NS.SCR level ($F(3, 84) = 4.07$, $p <= .01$, Greenhouse-Geisser corrected) (see Table 5 for the p-values of the post-hoc tests and Table 6 for means and standard deviations). The mean amplitude SCR and the EDA Symp findings showed no significant differences between the conditions.

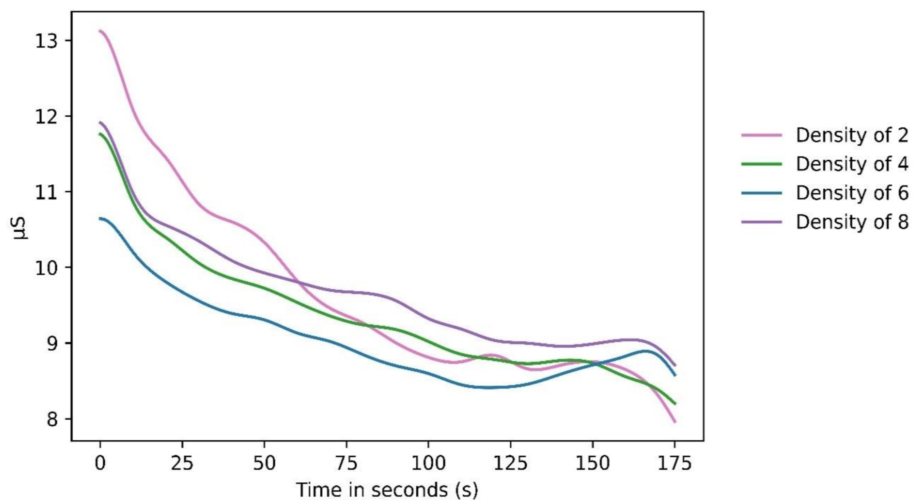


Figure 11: Plot of SCL scores averaged over all subjects for each density.

Table 5: Post-hoc tests: significant differences between the EDA parameters.

Comparison	NS.SCR	SCL
Density 2 – Density 6	p = .038	p = .0159
Density 6 – Density 8		p = .0012

Table 6: Means and standard deviations (in brackets) for all conditions.

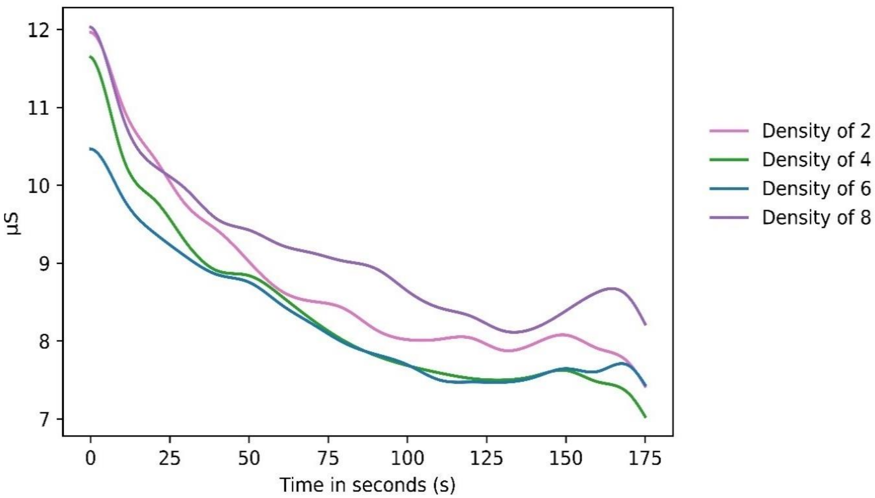
Condition	NS.SCR	SCL	EDA Symp	Mean SCR Amplitude
Density 2	28.38 (10.55)	11.53 µS (4.84 µS)	.073 (.08)	.002 µS (.0015 µS)
Density 4	26.10 (9.95)	10.51 µS (4.51 µS)	.05 (.06)	.0019 µS (.0014 µS)
Density 6	24.72 (8.69)	9.88 µS (3.98 µS)	.051 (.054)	.0018 µS (.0016 µS)
Density 8	25.10 (9.16)	10.70 µS (4.34 µS)	.074 (.1)	.0022 µS (.0019 µS)

Density 2 decreased the most. The run began at the highest value of 13.2 µS and decreased to the overall lowest value of 8 µS. There are several possible explanations for this strong variation. One is that subjects experienced Density 2 first and thus were nervous about what was coming next, which kept their arousal high. In a randomized experimental design where subjects do not always experience Density 2 first, this could mean that the high starting value of 13.2 µS is not reached. Alternatively, some form of adaptation might also be a factor. Perhaps being in the box with only one other person made the subjects feel particularly uncomfortable initially because it was not possible to hide behind someone else. Perhaps the habituation effect of having one other person in the box was also stronger because it was easier to get accustomed to one other person than to several people.

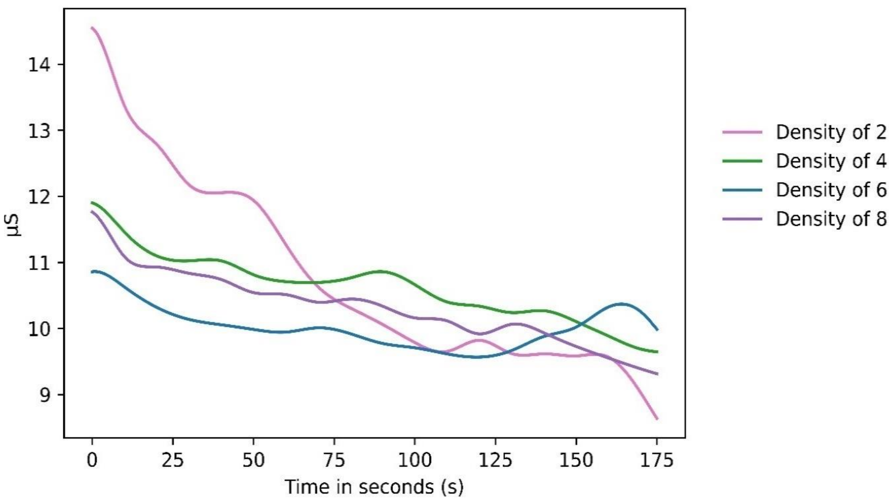
5.1.3.3 Effect of verbal communication

The effect of verbal communication was also tested in the experiments. The conditions of remaining silent and speaking could only be relatively compared to each other, since the two conditions had different test subjects (interindividual differences between EDA levels can be relatively large and, therefore, a direct comparison of the absolute levels between individuals was not advisable).

From Figure 12, it is noticeable that the EDA data trends differed by density and conditions. While in the silent condition, the SCLs were very similar for the different densities, the speaking condition showed a somewhat different pattern.



a)



b)

Figure 12: a) SCL scores averaged over all test subjects in the silent condition for all densities; b) SCL scores averaged over all test subjects in the speaking condition for all densities.

Looking at the silent condition data, the trends for Densities 4 and 6 were the same from second 35 to second 160. After second 160, Densities 4 and 6 separated. Overall, Densities 4 and 6 have the lowest slopes (Density 4: M = 9.9, SD = 3.7; Density 6: M = 9.48, SD = 3.27). Density 8 shows the highest SCL slope (M = 10.45, SD = 4.03), which means that Density 8 seemed to result in the most excited state. There was also a significant difference in the post-hoc test for Density 6 (M = 9.48, SD = 3.27) and Density 8 (M = 10.45, SD = 4.03, p = 0.04). Interestingly, the second highest slope is Density 2 (M = 10.43, SD = 4.1); being alone with another person without being allowed to speak also seemed to be stressful.

In the speaking condition, the ANOVA was significant ($F(1.28, 36.08) = 5.57$, $p = 0.025$), while the post-hoc test showed no significant difference. Nevertheless, Density 2 showed a different course than the other densities (Figure 12). The slope begins with the highest value and ends with the lowest value; it seems that talking to one other stranger was the most arousing. Over time, the level of arousal decreased, and the subjects became accustomed to the situation and verbal communication. Unlike in the silent condition, Density 4 was high and relatively stable. One explanation for this might be that a conversation with three people could be arousing because it is stressful. Another explanation may be that the communication itself is arousing. Compared to the silent condition, the arousal in Densities 4 and 6 did not drop as much, but in Density 6 the arousal increased from the lowest to the highest.

Comparing the density trends for the two conditions, it is evident that in the silent condition, Density 8 was associated with the highest SCL, while in the speaking condition, Density 4 led to increased SCL. In contrast, Density 4 had a similar trend to Density 6 in the remaining silent condition. Interestingly, Density 6 led to the lowest SCL in both conditions. It seems that Density 6 in both conditions created an environment that subjects perceived as even less arousing initially, due to either enough anonymity in the silent condition or enough communicators in the speaking condition, so that individuals who did not wish to speak did not feel compelled to do so. However, in the speaking condition, there seems to have been a change of perception at the end and the subject became more aroused. This may have been due either to the communication and loss of anonymity or to the density.

5.1.4 Discussion

Study 1 examined the correlation between density and arousal as well as that between density and the positioning of persons in personal space violations. For this purpose, a varying number of subjects gathered in a 1 m^2 box. While the subjects were in the box, an EDA measurement device measured arousal. All subjects pass through density conditions of two, four, six, and eight persons per m^2. The conditions also varied on whether subjects were allowed to communicate verbally and whether they were instructed to remain silent.

The overall performance of Study 1 showed that the experimental setup worked, and it is possible to collect EDA signals. It also showed that EDA data collection is possible in crowd research. Although the EDA method is difficult to use since it is susceptible to motion artifacts and environmental factors such as temperature, it is well suited to experimental designs such as that used in this study, which generated little motion because the subjects were standing still in a box. However, the effects demonstrated at the beginning and end of the experiments suggested that experiments with moving subjects may be more problematic.

Concerning the correlation between arousal and density, contrary to our hypothesis there was no significant decrease in comfort with increasing density in the box. I expected higher NS.SCR and SCL levels for higher densities. However, looking at the total time, I only found a significant difference between Densities 2 and 6. This finding fits our hypothesis, but what contradicts our hypothesis is that Density 6 had the lowest mean SCL overall. The mean SCLs for Densities 2 and 4 were higher; one possible explanation for this could be that being with five other people is less stressful than being with fewer people due to there being a certain level of anonymity. Density 8 might have been experienced as particularly stressful simply because of the physical closeness. Furthermore, when analyzing the questionnaires, the hypothesis was that subjects would describe densities higher than 4 as unpleasant. Indeed, the mean value of the densities (6.86) showed that this was only the case for densities above 6.

In sum, the results of Study 1 on arousal were not conclusive and require further investigation. Various factors should be considered in further research. First, 29 people was a relatively small sample for two conditions. The effects were not strong; therefore, more people are needed in future research to effectively identify the differences. Second, a major methodological problem was that baseline data were not collected. This would have allowed us to determine whether people in the tiny box were stressed and could have standardized the data so that I could have compared the data from the two conditions (speaking and remaining silent) in absolute rather than relative terms. Third, one possible explanation for the lack of difference between the densities could be that even a density of two persons per m² is high and not common in everyday life. Consequently, being together with even one other person in a space measuring 1 m² could be stressful and lead to increased arousal. What contradicts this theory was that Density 6 contained the lowest value for both SCL and NS.SCR. Nonetheless, future studies should explore sending only one person into the tiny box or building larger boxes in which densities of less than one person/m² can be created. It can be deduced from our initial results that increasing densities does not simply decrease comfort. The correlation is more complicated and probably mediated by the social situations created: a lower density might be more comfortable because more space is available, but it could also be less comfortable because it creates a direct interaction situation between two strangers. In situations with four subjects, a complex social choreography might take place that governs who needs to interact at what time and with whom. Larger densities reduce space and lead to involuntary body contact but, at the same time, they enable individuals to "disappear" into the crowd.

Time had an interesting, but unexpected effect on the data. Overall, all the SCL slopes show a downward trend, and this is particularly pronounced for Densities 2 and 8; the slopes for Densities 4 and 6 do not drop so sharply toward the end. A kind of adaptation seemed to take place up to a certain point. It would be interesting to examine whether the slopes for Densities 2 and 8 continue to drop during test runs of longer than 3 minutes. Questions to be answered are: Does this trend continue or does the adaptation cease after a certain time, and does the situation becomes more annoying and hence stressful again? and Do different density levels create different time-dependent trends if a longer time period is observed (e.g., 10 minutes)?

Furthermore, I need to consider what time domains are interesting and relevant to real-life scenarios. For example, a short-term stay in higher densities, such as in an elevator, usually lasts no longer than 50 seconds to 2 minutes. On the other hand, some situations in daily life lead to longer stays in higher densities, such as when traveling by train or standing in a waiting lane. We should examine how high train or waiting lane densities realistically become before we can examine their effect (and perhaps densities of four people per m^2 are already the maximum).

Measuring the subjective experience with a questionnaire did not work well in this study. In order to better capture subjective experiences, future questionnaires should be delivered after each round to obtain a more detailed assessment of the valence (the pleasantness or unpleasantness of an emotional stimulus) of being in the box at different densities. This will make it possible to compare valence and arousal.

The subjects who were allowed to speak believed that it made the situation easier to handle, while the subjects who had to remain silent were sure that speaking would have improved the situation. Previous research has indicated that when people remain silent, the density threshold perceived as unpleasant is lower than if they are allowed to speak. Therefore, I expected a higher NS.SCR level for the "remaining silent" condition; but this effect was not found. The visual comparison of the graphs for the two conditions shows that the slopes for the silent condition did not differ as much as those for the speaking condition. Also, it became clear that the relative relationships were different. Thus, in the speaking condition, the slope for Density 2 showed a special trend: standing together with another person and being forced to enter into verbal communication seemed to lead to a situation of enormous initial arousal. But when the situation continued, it seemed to lead to habituation and a clear decrease in the slope. Contrary to expectations, Density 4 (speaking condition) showed a constant trend, which did not decrease and was constantly the highest, compared to the slopes for Densities 6 and 8. One possible explanation for this may be that the conversation with three other people was very stimulating. Looking at the positions of the people in the box for Density 4, it was seen that four people formed a group and tried to interact as a group. This was potentially more engaging than with more subjects because it led to the building of subgroups and enabled some subjects to not get involved in the conversation. Another limitation of the data in the speaking condition was that talking can produce motion artifacts and more dynamic signals.

Examination of the silent condition data showed that SCL was the highest for Density 8, so in this condition, limited space seemed to be relevant. The second highest slope is Density 2, which could be explained by the lack of anonymity. Densities 4 and 6 had similar trends: in the silent condition, the slopes remain low, but in the speaking condition they increase noticeably, while the other slopes vary. Overall, there was an effect of verbal communication, which needs to be explored in more detail.

5.1.4.1 Suggestions for further experiments

To test whether the box itself has any effect on the subjects, I would like to repeat the experiment, but with lower densities and without the box (just with marks on the floor). It must also be noted that a sample of 29 people in a total of two conditions is relatively small; therefore, the experiments should be repeated with a larger sample. Another criticism is that the duration of the experiment toward the end showed a hypothesis-compliant progression for the different trends. It is worth considering how the length of the experiment duration affects the progression of the slopes in the graphs. To check this, the experiment would need to be repeated with some variation of the dwell time. If a result conforming to the hypothesis is seen at a longer dwell time, this would confirm that higher densities are indeed more arousing than lower densities. However, there is also initial excitement about being in an experiment at all to consider because the effect of the density was not evident until later. The effect of time on the relationship between density and well-being, and stress in general, was a particularly interesting finding. This should certainly be explored in further studies.

In Study 1, the effect of group composition was also not considered because of the small number of subjects. However, the gender breakdown and proximity to different genders might have affected the subjects' arousal levels. For example, women could feel more stressed by the proximity of men they do not know. To exclude this effect, the experiment should be repeated with single-gender groups and evenly-mixed mixed-gender groups. When repeating the experiment, as mentioned above, care should also be taken to collect a baseline for comparison and proper standardization of the data.

Moreover, the questionnaire should be changed and delivered after each round to obtain a more reliable subjective assessment of the experience. The striking downward trend at the beginning of the experiment should also not be ignored and the instruction effect should always be considered when planning the course of an experiment; in this context, for example, being given instructions might itself have led to increased arousal.

This experimental study shows that the relationship between comfort or stress and density is more complex than expected; both time and the social and communicative situation created in the box seemed to mediate the “higher density = higher stress” effect. This is directly relevant for applied contexts: densities are probably not “good” or “bad” in isolation but can be perceived as more or less pleasant depending on time, context, and social interaction.

5.2 Density: Study 2

Due to the methodological limitations identified in Study 1 with the tiny box, the experimental setup was repeated as part of the CroMa Project experiments in October 2021. The time in the box was extended, the number of boxes was increased to four, and the density variation was extended to include a density equal to 1 condition to generate a baseline. In addition, after participating in each density condition, all the subjects rated (on a scale of 1 to 7) their perceived reduction in comfort level due to that density condition.

5.2.1 Hypotheses

1. Density will influence the excitation parameters (SCL, EDA Symp, SCR amplitude, NS.SCR level).
2. Perception of physical proximity to others will influence the arousal parameters (SCL, EDA Symp, SCR amplitude, NS.SCR level).
3. Perceiving oneself as a confounder will influence the excitation parameters (SCL, EDA Symp, SCR amplitude, NS.SCR level).
4. The number of subjects perceived as most uncomfortable will impact the arousal parameters (SCL, EDA Symp, SCR amplitude, NS.SCR level).
5. Density will impact the subjective evaluations given after each stay in density.
6. There will be a correlation between the excitation parameters (SCL, EDA Symp, SCR amplitude, NS.SCR level) and subjective evaluations, given after each stay in density.

7. The “speaking” condition will result in lower excitation values (SCL, EDA Symp, SCR amplitude, NS.SCR level) compared to the “remaining silent” condition.
8. Within the “speaking” and the “remaining silent” conditions, the density, proximity of other people, and confounding factors will influence the arousal parameters (SCL, EDA Symp, SCR amplitude, NS.SCR level) and the subjective evaluations.
9. Subjects in the “remaining silent” condition will find proximity to others more uncomfortable. In addition, they will find smaller numbers of people unpleasant and perceive themselves as a disruption factor.
10. After an initial decrease in SCL, a longer stay in higher densities will ultimately lead to a significant increase in SCL for all densities.

5.2.2 Materials and Methods

5.2.2.1 Subjects

The subjects for Study 2 were recruited as part of the large-scale CroMa Project experiments. During the CroMa experiments, the subjects went through a “round robin” of several experiments; 45 minutes were allocated for each experiment, then the group changed. Participating subjects were divided into three experimental groups, each ranging in size from 80 to 120 people. Each group went through the different experimental locations twice. From each experimental group, 16 people (eight in the morning and eight in the afternoon) participate in the Study 2 Tiny Box experiments. To avoid habituation effects, each person was allowed to participate in the Tiny Box experiment only once. The sample included a total of 96 subjects. Of these, 16 subjects were excluded due to incidents during the experimental procedure, such as being photographed by the press, which could lead to data bias. The collected EDA data from the remaining 80 subjects were checked for artifacts. Due to poor data quality (zero lines and values below 1 µS or extreme outliers), the dataset was reduced again by 16 individuals, leaving a total sample size of 64. The mean age of the subjects was 24.39 (SD = 5.52) years. The overall intended gender distribution was 50% female and 50% male, but by excluding some subjects, there were 34 (53.1%) females to 30 (46.9%) males.

5.2.2.2 Procedure and experimental paradigm

The experimental setup was like that of the Study 1 Tiny Box experiment, but this time, instead of two boxes, four boxes were filled to ensure greater experimental efficiency. The boxes were placed in an alcove in the Mitsubishi Electric Hall that could not be directly seen by the other subjects; this was to avoid subjects “feeling observed” and to avoid distorting the physiological data (Figure 13). The structure of the boxes remained the same. That is, they had three fixed sides and a door. The height of the box was 150 cm, and cameras filmed the experiments from above. As the experiments took place during the COVID-19 pandemic, the subjects wore a mask as a safety measure.

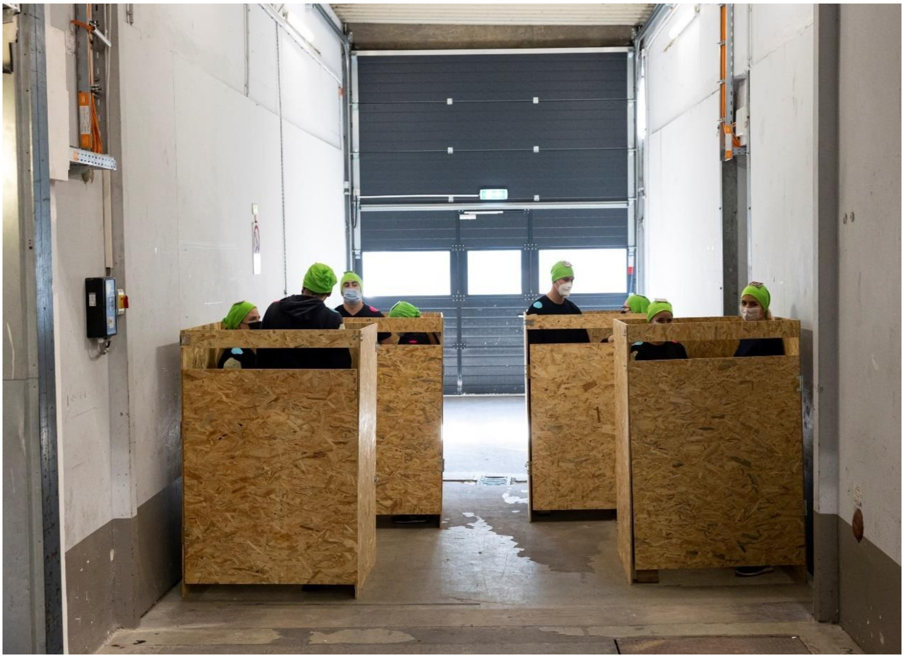


Figure 13: Picture of the experimental setup of the Study 2 Tiny Box experiment in Düsseldorf. The picture shows two persons per m² (Density 2).

The subjects had EDA Move 4 sensors with two electrodes attached to their non-dominant hand directly after they separated from the large experimental group. The subjects completed a questionnaire about the demographic information and frequency of being in crowds or rush hour traffic directly after they entered the hall during the general registration.

The subjects experienced five different levels of density (Figure 14): one, two, four, six, and eight people/m². Not every subject went through the density conditions in the same order, but they all went through every density condition. Only the first and last density conditions were the same for each subject; the first was two subjects/m², and the last was four subjects/m². The duration of each experimental run was 5 minutes. After each experimental run, the subjects left the boxes, and the subjects completed a short questionnaire about their experiences in the box. No attention was paid to the gender distribution when the boxes were filled. As in Study 1, there were two conditions: speaking and remaining silent. Subjects were allowed to communicate verbally while in the box in the speaking condition, but not in the remaining silent condition. At the end of the experiment, the subjects again completed a questionnaire about their whole experiences in the box.

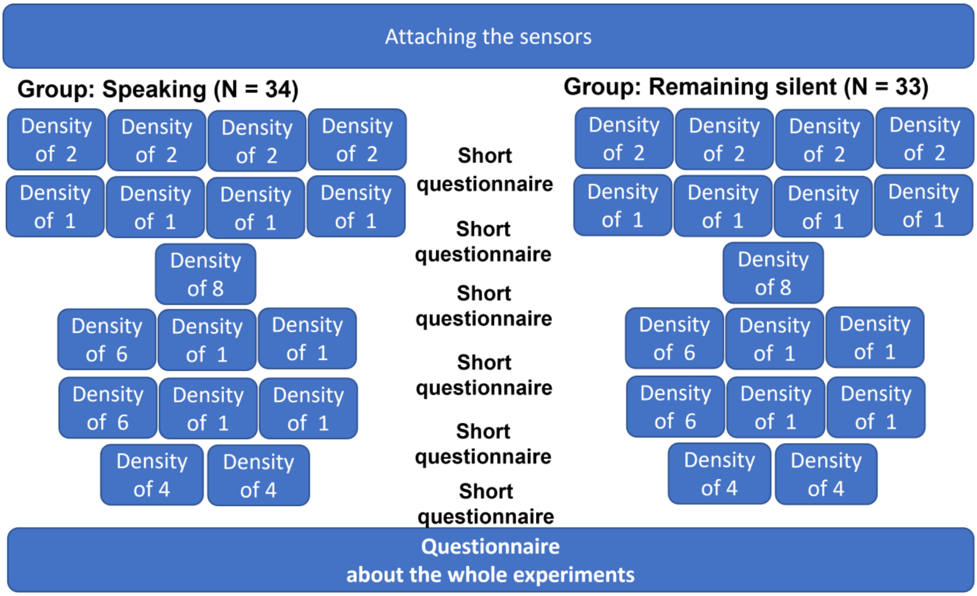


Figure 14: Study 2 experimental procedure. This shows the split into two conditions (speaking, remaining silent) and the number of density conditions and their loadings.

5.2.2.3 Questionnaire

In addition to collecting demographic data, a questionnaire was used after the experiment to ask subjects about their experiences and feelings during the experiment. Responses were recorded on a 7-point Likert scale (1 = strongly disagree, 7 = strongly agree) (see Table 7). In addition, subjects who were not allowed to speak during the experiment were asked whether they thought it would have made the situation easier if they had been allowed to speak. Subjects also indicated which of the densities was the most uncomfortable for them (Figure 15). After each stay in a density, subjects assessed how unpleasant they found the stay. They also draw a time curve showing how their sensation changed during the run.

Table 7: Questionnaire results for the whole group (overall) and the different conditions (remaining silent, speaking).

	Item	Overall: Mean (SD)	Remaining silent: Mean (SD)	Speaking: Mean (SD)
1	I perceived myself as a disruptive factor over the course of the experiment.	2.35 (1.76)	2.59 (1.94)	2.07 (1.51)
2	The physical proximity to other test subjects made me uncomfortable.	3.73 (1.84)	4 (1.78)	3.41 (1.90)
3	Communication would have made the situation more pleasant.	5.39 (2.09)	5.06 (2.24)	5.79 (1.85)

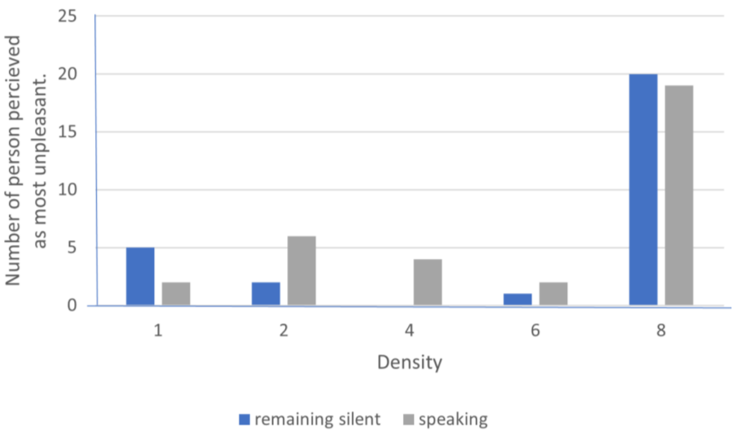


Figure 15: Density (number of people in the box) that made subjects uncomfortable: absolute frequencies for the remaining silent and speaking conditions.

5.2.2.4 Statistical analysis

The differences between the different experimental conditions were tested using one-way analysis of variance (ANOVA) with repeated measures. The parameters that were compared were EDA Symp, SCL, SCR amplitude, and NS.SCR level. Each of the subjects experienced each density condition for 5 minutes. The period after the experimenter closed the door and the moment when the experimenter re-entered the camera image were used to calculate the time intervals.

Due to the sample size being greater than 25, no test for normal distribution needed to be performed for the ANOVA test, as this can be assumed (Wilcox, 1996). After ANOVA, the parameters were tested for differences in each condition using post-hoc t-tests. The Bonferroni method for multiple testing was used to adjust for alpha error. To determine the effect of attitude (as collected by the questionnaire at the end of each experimental run), the individual items were included as an interaction factor. Due to the very uneven distribution of the answers, they were split into two categories: agree (4 or more on the rating scale) or disagree (3 or less on the rating scale).

When it came to the group comparisons between the different assessments and experimental conditions, the SCL scores were z-standardized at the one person per/m^2 condition so that individual variation in the baseline SC level was balanced and the data were comparable (Boucsein, 1988).

5.2.3 Results

5.2.3.1 Results: Questionnaire

Comparing the subjective assessment ratings of the densities to the experience of the density, significant differences were found between the densities (F (3.17, 187.31) = 15.86, $p < .0001$). The Tables 8 and 9 show the post-hoc comparisons and means and standard deviations. No interaction effects were found for the other questionnaire data or the speaking and remaining silent conditions. For the subjective ratings within the speaking group, there were significant differences (F (4, 120) = 11.66, $p < .001$). For the remaining silent group, there was a main effect for density (F (2.72, 76.27) = 6.24, $p = .001$) (For post-hoc test see Table 10 and 11).

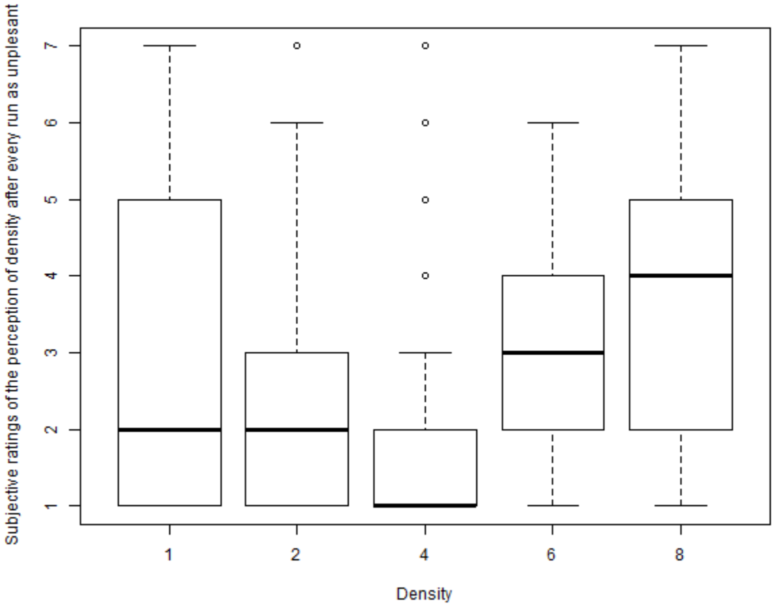
Table 8: Post-hoc comparisons: significant differences between the EDA parameters.

Comparison	SCL	EDA Symp	Mean SCR Amplitude	Subjective rating
Density 1 – Density 2	p < .001	p = .046	p = .011	
Density 1 – Density 4	p = .018			
Density 1 – Density 8				p < .001
Density 2 – Density 4	p < .001		p = .0021	
Density 2 – Density 6	p < .001			
Density 2 – Density 8	p = .001			p < .001
Density 4 – Density 6	p = .03			p < .001
Density 4 – Density 8	p < .001		p = .0043	p < .001
Density 6 – Density 8				p < .001

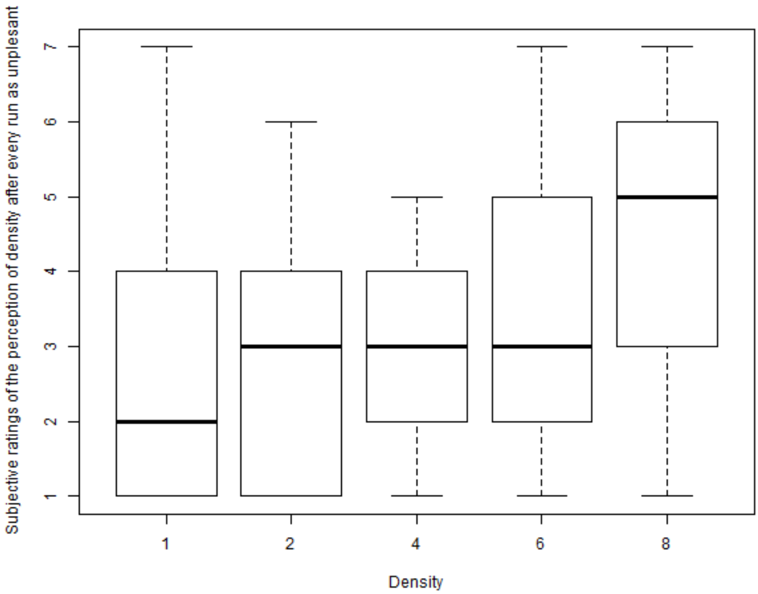
Table 9: Means and standard deviations (in brackets) for all conditions.

Condition	NS.SCR	SCL	EDA Symp	Mean SCR amplitude	Subjective ratings
Density 1	16.52 (8.96)	8.49 µS (4.16 µS)	.05 (.09)	.00086 µS (.00091 µS)	2.67 (1.96)
Density 2	15.97 (8.61)	7.22 µS (3.44 µS)	.03 (.04)	.00056 µS (.0006 µS)	2.72 (1.64)
Density 4	16.47 (9.06)	9.49 µS (4.58 µS)	.06 (.09)	.00092 µS (.00094 µS)	2.65 (1.57)
Density 6	15.94 (8.94)	8.59 µS (3.51 µS)	.04 (.06)	.00073 µS (.00079 µS)	3.37 (1.69)
Density 8	16.05 (9.86)	8.21 µS (3.51 µS)	.03 (.05)	.00064 µS (.0007 µS)	4.19 (1.81)

There were also no differences within the speaking and remaining silent conditions for perceptions of proximity, perceiving oneself as being a disruptive factor, and the number of persons in the box. Also, both groups equally assumed that communication made the situation easier. When looking at the absolute frequencies for how many people in the box made the experience unpleasant, it was noticeable that in both conditions, subjects perceived Density 8 as the most unpleasant (Figure 16).



a)



b)

Figure 16: Subjective assessment after each experimental run for the two main conditions: a) speaking, and b) remaining silent. The median is marked with a bold line.

5.2.3.2 *Results: Skin conductance (SC)*

When qualitatively examining the SCL graphs, it is noticeable that the slope for Density 2 is consistently the lowest, which shows that this condition led to the lowest physiological excitation. In contrast, the slope for Density 4 consistently shows the highest excitation values (Figure 17). The slopes for Densities 1, 6, and 8 are very close to each other. It is also noticeable that the slope of Density 8 is the lowest when comparing the three conditions, while Density 6 is consistently the highest. Overall, all the slopes drop over the course of the experiment.

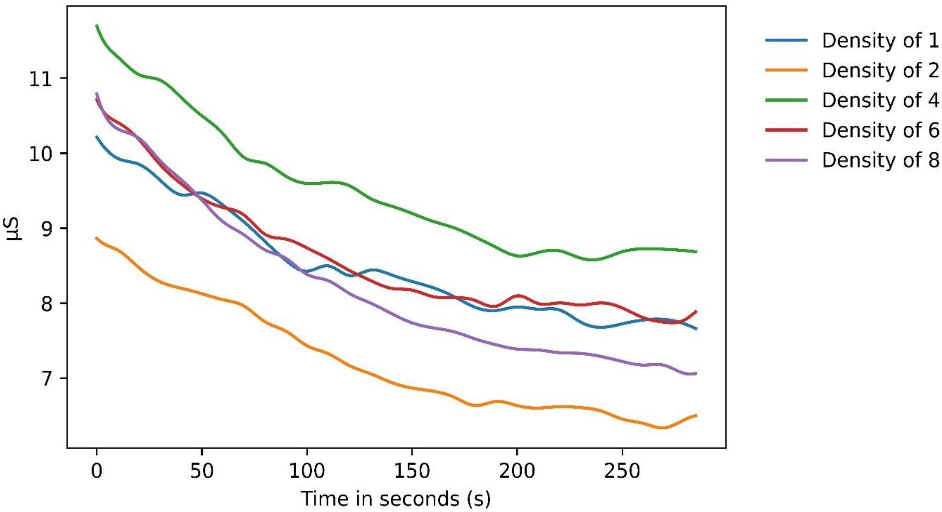


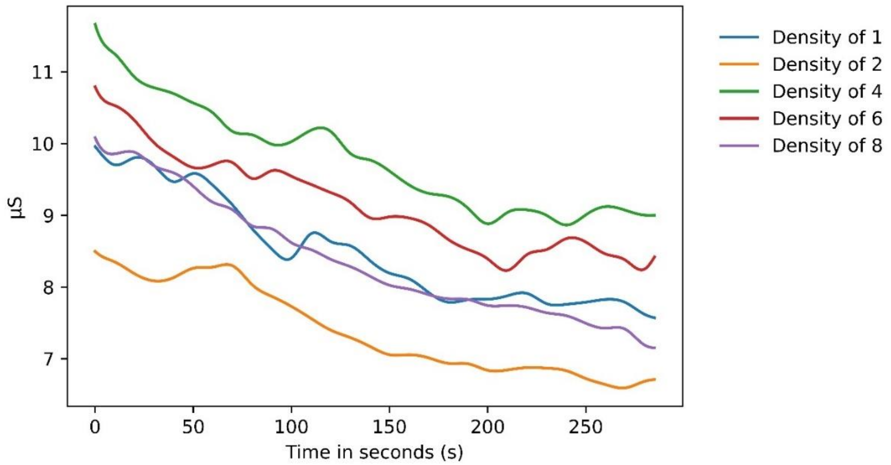
Figure 17: Plot of SCL scores averaged over all subjects for each density.

Looking at the data quantitatively, it is noticeable that density had a significant effect on (SCL, EDA Symp, and SCR amplitude). Thus, for SCL, a main effect of density was found ($F(2.96, 186.38) = 16.31$, $p < .0001$, Greenhouse-Geisser corrected). For SCR amplitude, a main effect for density was also found ($F(3.22, 202.71) = 5.95$, $p < .0001$, Greenhouse-Geisser corrected). The significant differences for the post-hoc tests and the mean and standard deviations are given in Tables 8 and 9. The EDA Symp parameter shows only one main effect between densities ($F(2.68, 168.57) = 4.01$, $p < .011$, Greenhouse-Geisser corrected).

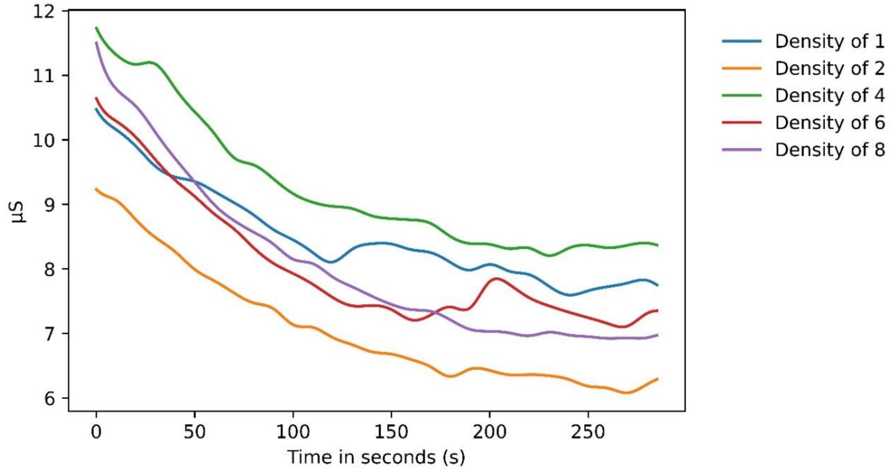
5.2.3.3 *Effect of verbal communication*

Considering the two conditions “speaking” and “remaining silent”, it is noticeable that the conditions did not influence the different stress parameters. An interaction effect ($F(4, 248) = 3.26$, $p < .012$) between density and conditions was only found for NS.SCR. Looking at the interaction plots, it is noticeable that there was a fall in SCR between Densities 1 and 2, for the remaining silent condition, but an increase for the speaking condition.

Qualitative inspection of the SCL graphs for the speaking and remaining silent conditions show that the slopes for the individual densities are almost identical (Figure 18). Density 2 and Density 4 are identical in position, while Densities 1, 6, and 8 are slightly redistributed. It is noticeable that remaining silent in Density 1 has a higher trajectory compared to Density 8 and Density 6, while in the speaking condition, Density 1 has a similar height to Density 8. In the speaking condition, Density 6 is consistently the highest of Densities 1, 6, and 8.



a)



b)

Figure 18: SCL scores averaged over all subjects for each density: condition a) speaking, and b) remaining silent.

The quantitative examination of the data from the remaining silent group revealed that density had a significant effect on EDA scores (SCL and amplitude). Thus, for SCL, there was a main effect of density ($F (4, 132) = 8.36, p < .0001$). There was no interaction effect between density and proximity. For SCR amplitude, a main effect of density was found ($F (2.86, 94.53) = 3.32, p = .025$). The NS.SCR comparison was not significant, although there was a significant post-hoc comparison between Densities 1 and 6. The same was found for EDA Symp. The significant post-hoc test differences and the means and standard deviations for the speaking and remaining silent conditions can be found in Tables 10 and 11.

Table 10: Post-hoc tests: significant differences between the EDA parameter conditions.

Remaining silent					
Comparison	NS.SCR	SCL	EDA Symp	Mean SCR amplitude	Subjective rating
Density 1 – Density 2		p = .0024			
Density 1 – Density 6	p < .024				
Density 1 – Density 8					p < .001
Density 2 – Density 4		p < .001			
Density 2 – Density 8		p =.026			p = .003
Density 4 – Density 8			p < .05		p < .001
Density 6 – Density 8					p = .005
Speaking					
Density 1 – Density 4		p = .011			
Density 2 – Density 4		p < .001		p = .029	
Density 2 – Density 6		p = .001			
Density 2 – Density 8					p < .001
Density 4 – Density 6					p = .0039
Density 4 – Density 8		p = .032			p = .0023

Table 11: Means and Standard deviations (in brackets) for all conditions.

Remaining silent					
Condition	NS.SCR	SCL	EDA Symp	Mean SCR Amplitude	Subjective ratings
Density 1	18.09 (9.93)	8.55 µS (3.44 µS)	.04 (.07)	.00085 µS (.00086 µS)	2.58 (1.77)
Density 2	14.97 (8.04)	7 µS (2.13 µS)	.03 (.05)	.00053 µS (.00066 µS)	2.97 (1.7)
Density 4	15.26 (9.49)	9.13 (4.11)	.05 (.08)	.00086 µS (.0010 µS)	3.03 (1.26)
Density 6	14.74 (9.25)	8.01 (3.02)	.03 (.07)	.00062 µS (.00076 µS)	3.52 (1.86)
Density 8	15.56 (10.2)	8.01 (3.01)	.02 (.04)	.00063 µS (.00083 µS)	4.5 (1.86)
Speaking					
Density 1	14.73 (7.5)	8.41 µS (4.91 µS)	.07 (.11)	.00088 µS (.00098 µS)	2.77 (2.18)
Density 2	17.1 (9.23)	7.47 µS (4.51 µS)	.02 (.02)	.00059 µS (.00052 µS)	2.43 (1.55)
Density 4	17.83 (8.49)	9.89 µS (5.09 µS)	.07 (.11)	.00099 µS (.00083 µS)	2.21 (1.78)
Density 6	17.3 (8.51)	9.25 µS (3.95 µS)	.04 (.04)	.00086 µS (.00083 µS)	3.2 (1.49)
Density 8	16.9 (9.6)	8.44 µS (4.04 µS)	.03 (.05)	.00065 µS (.00054 µS)	3.83 (1.7)

In the speaking group, the parameter SCL was significantly different from density (F (1.96, 56.94) = 9.62, $p < .001$). The mean SCR amplitude level was also significantly different from density (F (2.88, 83.45) = 3.07, $p = .034$). The parameter EDA Symp showed a main effect for density (F (2.24, 64.99) = 2.65, $p = .037$). However, the post-hoc tests show no significant differences between conditions. For the EDA parameters, neither proximity of others, perceiving oneself as disruptive, nor the number of people perceived as most uncomfortable showed an influence.

5.2.4 Discussion

This study (Study 2) is an extension of Study 1 (see Section 5.1). The methodological limitations discussed in Study 1, such as considering the lowest possible density of 1 and expanding the sample size for the two conditions, were addressed in this study. By collecting Density 1, a baseline was collected. Standardizing the data at the baseline allowed for quantitative comparison between the remaining silent and speaking groups. Furthermore, because of the more hypothesis-compliant shape of the mean SCL graphs in Study 1 (the higher the density, the higher the values; see Figure 11) at the end of the experimental runs, the effect of time on the tonic component was controlled here with a longer experimental run. The use of a new questionnaire with a direct query about the subjects' perceptions after each experimental run allowed for a better assessment of the subjective experience of density.

Overall, Study 2 also showed that the EDA is a good measure for the measuring arousal state of people in crowds. Like Study 1, this study also showed an interesting picture in that physiological arousal does represent stress experience and this differs with different densities. However, the generally valid saying "the denser, the more stressful," as hypothesized by Sokol (1978), does not apply.

Despite this, the results showed that density influenced the excitation parameters. Thus, the hypothesis about the influence of density on EDA was confirmed. Nevertheless, it should be noted that the found differences for the individual densities were different than expected. For example, a density of four people on the 1 m² box was the most arousing, while a Density of 2 led to the least arousal; this was contrary to what was expected (i.e., that a density of 8 would lead to the most significant arousal and a density of 1 would lead to the least). A possible explanation for this finding is that the data were subject to sequence effects. Moreover, regarding the high arousal parameters in the Density 4 condition, increasing agitation in the experiment environment may have influenced the arousal parameters because some subjects often moved to the next experiment area earlier than the stipulated 45 minutes. However, the low arousal at Density 2 could also be explained by feelings of not having to go through the situation alone, thus representing a kind of reassurance. The fact that standing in the box alone was perceived as strange could explain the higher arousal levels in Density 1. However, the continuously collected questionnaire data suggested that subjectively, the subjects perceived Density 8 as the most uncomfortable, which was in line with expectations.

As regards the discrepancy between the subjectively assessed experiences of density and the arousal scores, it can be argued that the expectation and understanding that densities of 6 and 8 people are unpleasant is what led to a more cognitively driven result. Furthermore, the discrepancy found supports the suggestion that the ordering of the density conditions had an influence and that the increased arousal may not have been associated with the crowding in the box, but with the environmental unpleasantness. Another possible explanation is that the subjects in the box wore masks because of the COVID-19 pandemic. With masks comes difficulty in recognizing and assessing the emotions of other people (Grahlow et al., 2022). This might have led to increased cognitive effort due to group size at Density 4. Due to the easily manageable group size, it can be assumed that the subjects perceived each of the other three persons individually. In the Density 6 and Density 8 conditions, however, they may have switched to a different strategy to reduce the increased cognitive processing effort. Perhaps they no longer tried to accept the individuals in the box but switched to a kind of "group perception" (e.g., dehumanization of the other people in the box). This may have resulted in lower arousal levels.

The influence of the speaking and remaining silent conditions on the arousal parameters and the density experience ratings were considered. Contrary to expectations, no differences were found between the groups. While it was expected that the remaining silent condition would be perceived as more stressful than the speaking condition, an interaction effect was only found for NS.SCR, which decreased in the remaining silent condition but increased in the speaking condition. This may have been related to the fact that subjects in the speaking condition produced more NS.SCR at higher densities due to the speaking itself or due to the topic of the conversation. Overall, however, there is no decisive explanation for this finding, and it could simply have been a chance finding. Furthermore, no differences were found for the arousal parameters or in the subjective evaluation, even though the subjects in both groups subjectively reported that the situation was/would have been easier to bear through communication. There were also no differences for perceived proximity to others or perceiving oneself as being a disruptive factor; however, a trend towards higher values for these variables was seen in the remaining silent group. This may be an indicator that using a larger sample will result in significant effects.

Individual analyses of the "speaking" and "remaining silent" conditions

In addition to the overall data, the speaking and remaining silent data were examined individually. Again, it was noticeable that in both conditions, only density influenced the arousal parameters and subjective ratings. The distribution of the slopes was similar for both conditions (see Figure 18).

Regarding the influence of experiment duration on each condition, an increase in the average SCL was expected for longer density stays; however, a linear fall of the slopes over time was found for both the speaking and remaining silent conditions. This suggests an adaptation effect to the situation; such an effect was also assumed in the studies of Zhao et al. (2019) and Mavros et al. (2022). To exclude this effect, their experiments were of short duration. Thus, the two studies only focused on short-term experiences of density.

5.3 Conclusion: Studies 1 and 2

The results found in Studies 1 and 2 show that density, especially social density, is a very complex concept. In summary, the Tiny Box experimental design allows for the elicitation of arousal in density. However, it also shows how complex the experience of density is. The lack of correspondence between subjective evaluation and physiological arousal in Study 2 indicates that there is a difference between arousal and evaluation of the experience at high densities. However, it must also be considered that asking about subjective experiences of stress with the statement "I found the density unpleasant" does not make any statement about arousal. With this statement, only the valence, i.e., whether the situation/stimulus was perceived as positive or negative, was determined. Lazarus and Folkman (1986) proclaims that subjective perceptions need not always be identical to the objective parameters and/or the resulting physiological reaction. However, both forms of assessment agreed in both studies, and it was determined that a density of 8 was the most unpleasant.

Through these studies, it has also become clear that experiments that are as controlled as possible are needed to accurately study the pure influence of density on excitation. The physiological arousal results are consistent with Stokols's (1978) argument that density is not synonymous with crowding. However, this was not true for the subjective evaluation findings, which are consistent with the general understanding that the denser a crowd, the more stressful it is. Overall, it also appears that violations of different personal space domains do not make a difference. However, it has to be considered that the experiment design only investigated intimate distance, therefore no clear statement can be made about the correlation. For further studies, it could be interesting to examine the positioning of the persons to each other (Hirschauer, 1999; Konya & Sieben, 2023; Küpper & Seyfried, in progress).

A limitation of these experiments could arise because the subjects already expected the positioning to be dense. Burgoon and Jones (1976) theorized that the expectation of density influences stress development. According to Stokols (1978), in a study situation, the subjects are not expected to think that their own space will be intentionally violated, as it could lead to aversive behavior. Also, due to the stationary nature of the Tiny Box situation and the low pressure involved, it can be assumed that the subjects did not feel threatened.

The decrease in physiological arousal found in both studies could speak for a kind of coping strategy. Because the situation remained constant and the subjects did not associate the initial arousal with the narrowness of the situation, arguably, a kind of coping occurred. As a result, the arousal was lowered. This assessment is supported by the stress theory of Lazarus (1986), who saw the evaluation of the situation as an effective measure for lowering the autonomously occurring arousal. This could explain the discrepancy between the subjective and objective stress parameter findings. The evaluation of the situation as not very threatening could have led to a corresponding cognitive evaluation, however, which only influenced the EDA parameters after a certain latency period.

6 Studies on Walking

The studies described above focus on the experience of density while waiting in a stationary context and show that the statement “the denser, the more stressful” does not apply. In addition to waiting, people also walk in traffic systems and move in crowds, and this is central to our lives. Thus, in addition to the density factor, another influencing factor is speed. If we consider this connection, the question arises as to how the simultaneous influence of speed and density affects the stress experience. The studies presented in this section consider on the one hand the factor speed, and on the other hand, the connection between density and speed. Two studies distinguished the relationship between walking speed and arousal from the relationship between density-dependent walking speed and arousal. In the first study (Study 3), the effects of predetermined changes in walking speed from “normal speed” to significantly slower walking speeds were examined. In addition, the effect of a freely chosen speed compared with a given speed on arousal was examined, as this is a key feature of the PLOS criteria of Weidmann (1993). The second study (Study 4) investigated the relationship between density and speed using a well-established experimental setting in pedestrian research. The single file experiments, in which more or fewer subjects walk in a defined oval and adjust automatically the walking speed to the filling of the oval (Seyfried et al. 2005). Essential parts of this chapter will be published in the article Beermann and Sieben (in progress).

6.1 Walking Speed: Study 3

6.1.1 Hypotheses

1. Walking at a freely chosen walking speed is less stressful and will, therefore, show lower skin conductivity than a given walking speed.
2. Enforcing slower walking speeds using preset walking speeds (1.42 m/s, 0.86 m/s, 0.31 m/s, and 0.19 m/s) will lead to increased SC.
3. Persons who normally walk fast (measured by their freely chosen walking speed) will be more stressed under slower walking conditions and, therefore, will have higher SC values.
4. Persons who want to overtake (as surveyed by a questionnaire) will have higher SC values under slower walking conditions.

6.1.2 Materials and Methods

6.1.2.1 Subjects

Twenty-five subjects participated in Study 3. The subjects were recruited through calls in university lectures, and university Facebook groups and bulletin boards. Consequently, this was a student sample. Each subject received €10 for participation.

After checking the EDA signals for artifacts such as null lines or extreme fluctuations due to motion or contact problems with the electrodes, I excluded eight subjects from further analysis, which left a total of 17 subjects. As this was a student study, the average age was 27.59 years. Of the 17 subjects, 12 (71%) were female and five (29%) were male. The gender distribution was not evenly; since I assumed no gender effects, there was no special consideration of gender in the design or analyses. Each of the subjects signed an informed consent form after being informed how the experimental procedure would work. All the methods were performed in accordance with the Declaration of Helsinki.

6.1.2.2 Procedure and experimental paradigm

The study took place at the Ruhr University in Bochum, Germany. Due to the COVID-19 pandemic, experiments with crowds were difficult, so the experiments were conducted outside and with a maximum of five subjects at a time. The subjects wear masks in all runs. The subjects get the EDA sensors after arrival and then completed a demographic questionnaire (see Figure 19 for the study procedure). A course of 90 m long was set for the experimental conditions (see Figure 10). First, the experimenter show the course to the subjects. Then the subjects walked the course alone while their time was measured to record their free walking speed. Subsequently, a baseline for the EDA was determined. For this, the subjects stood still on the spot for 3 minutes. For the "standardized" given speeds, the subjects walked around the course again as a test leader walked ahead of them. The test leader kept track of the speed using a metronome and floor markers with different distances; they crossed the distance between two floor markings in two beats of the metronome. Therefore, the greater the distance, the faster the speed. The group of subjects walked behind each other at 1.5 m intervals. Overtaking was not allowed. The specified walking speeds along the various parts of the course were 1.42 m/s, 0.86 m/s, 0.31 m/s, and 0.19 m/s. Each speed was walked for 3 minutes. The subjects then completed a questionnaire about their sensations during the experiments. The procedure was approved by the Ethics Council of the DGPs.

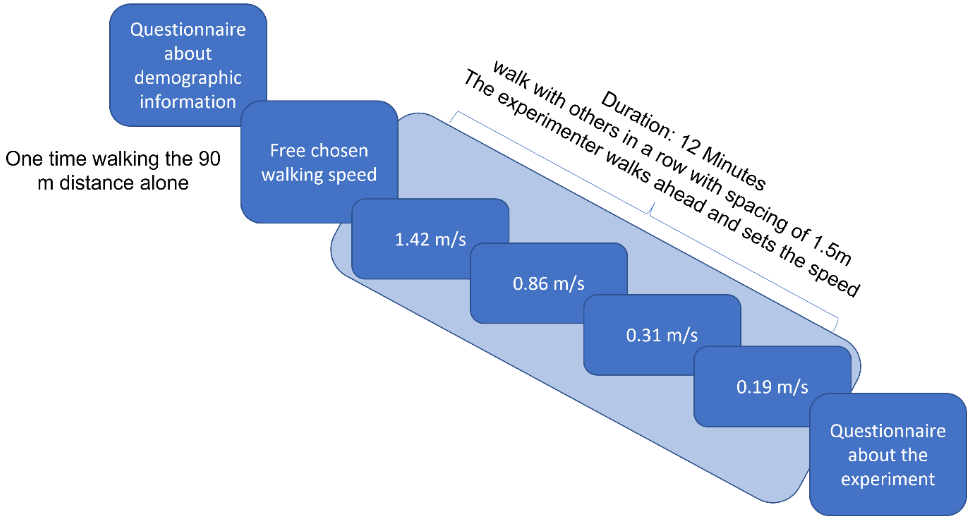


Figure 19: Study 3 experimental procedure.

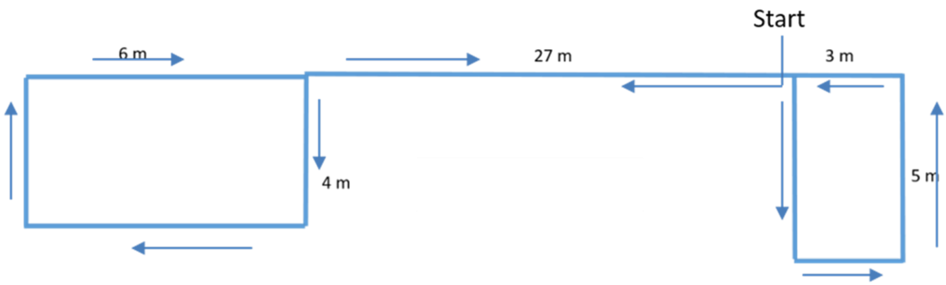


Figure 20: The experimental course: the subjects walked around it twice, once on their own and then following the test leader.

6.1.2.3 Questionnaire

In addition to collecting demographic data, subjects were interviewed after the experiment. The interview items can be found in Table 12 together with the means and standard deviations for the subjects, who walking faster than 1.39 m/s (mean fast) and who walked slower than 1.39 m/s (mean slow). The interview items referred to the subjects' experiences or sensations during the experiment. Responses were mapped using a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). In addition, subjects who rated the very slow speed (0.19 m/s) as unpleasant were asked what the reason was. Subjects also indicated which of the four given speeds was the most unpleasant for them in terms of compliance (Figure 21).

Table 12: The questionnaire items with corresponding means and standard deviations.

	Item	Overall mean (SD)	Group mean fast (SD)	Group mean slow (SD)
1	I felt observed over the course of the experiment by other people (not part of the experiment).	2.06 (1.09)	2 (1)	2.12 (1.25)
2	I felt the need to overtake the person in front of me.	2.88 (1.58)	2.44 (1.74)	3.38 (1.3)
3	The very slow speed was uncomfortable for me.	3.47 (1.12)	3.11 (1.45)	3.88 (0.35)

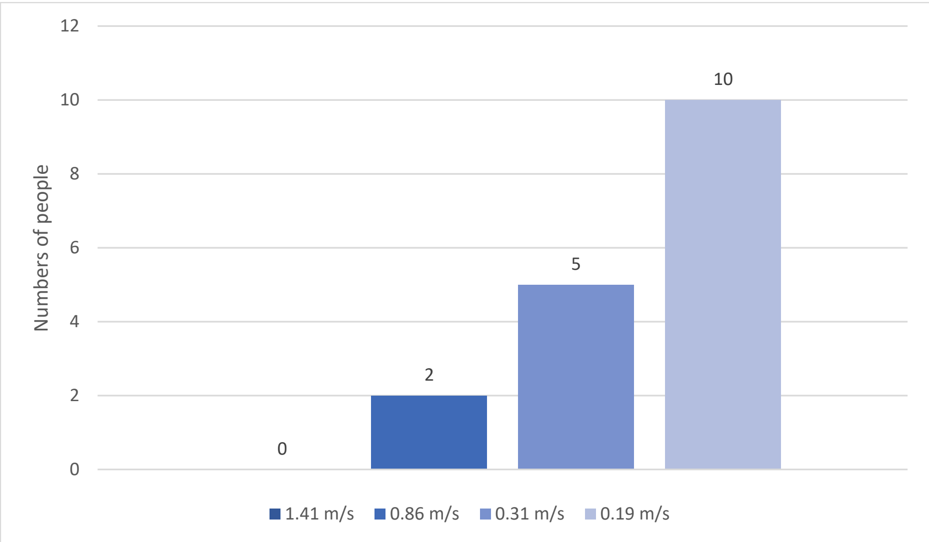


Figure 21: Subjects' subjective perceptions of which walking speed was the most uncomfortable.

6.1.2.4 Statistical analysis

The hypotheses were formulated in a one-sided manner, and the significant differences between the different experimental conditions were tested using one-way analysis of variance (ANOVA) with repeated measures. The parameters were EDA Symp, SCL, NS.SCR, and SCR Amplitude. The subjects performed every condition for 3 minutes; to compare the freely chosen walking speeds, the duration of the fastest subject was used to obtain an equal time interval for all subjects. In addition, the total walking times for each 3-minute experimental condition were compared.

For the ANOVA test, normal distribution was checked using the Kolmorov-Smirnov test. Non-parametric tests were used for the normal distribution violations. The individual conditions were then tested using post-hoc t-tests, applying the Bonferroni method for multiple testing.

In addition to examining the influence of the habitual walking speed of every subject, the normal walking speed was also collected and examined in the condition "freely chosen walking speed." For this purpose, the subjects were divided into two groups (fast and slow). All subjects walking faster than 1.39 m/s in the free walking speed condition were assigned to the fast group. The groups were examined for the differences between the pre-set walking speeds within the group. Also, the differences between the fast and slow groups were also compared. For this, I used a mixed model in which speed was included as the independent variable and freely chosen speed was included as the mediator. A second mixed model was used to mediate the desire to overtake the front-runner on the EDA parameters. For the between-group comparisons, the EDA data were standardized beforehand, otherwise, they would not have been comparable due to the individual baseline values for the subjects.

6.1.3 Results

6.1.3.1 Results: Questionnaire

The means and variances for the individual questionnaire items collected at the end of the experiment can be found in Table 12. To investigate the influence of freely chosen speed on the perceptions of the experiment, we divided the sample into two groups (fast and slow; see above). We found no significant difference between perception assessments for very slow speed and the desire to overtake. Nevertheless, the mean value trends indicated that a fast freely chosen pace leads to a greater desire to overtake and a more uncomfortable feeling when walking slowly (see Table 12). The effect size was moderate (Cohen's $d = 0.57$). The individuals who found the slowest condition most uncomfortable stated that they also found it difficult to maintain balance and considered walking slowly a waste of time.

6.1.3.2 Results: Skin Conductance (SC)

When qualitatively examining the SCL data over time, it was noticeable that the level of arousal at the freely chosen speed was significantly higher than at the externally imposed speeds. In addition, there was a clear separation between all the conditions (Figure 22). Looking at the SCL values, we found some differences over time (Friedman test: X^2 (4) = 38.17, $p < .001$) (Tables 13 and 14).

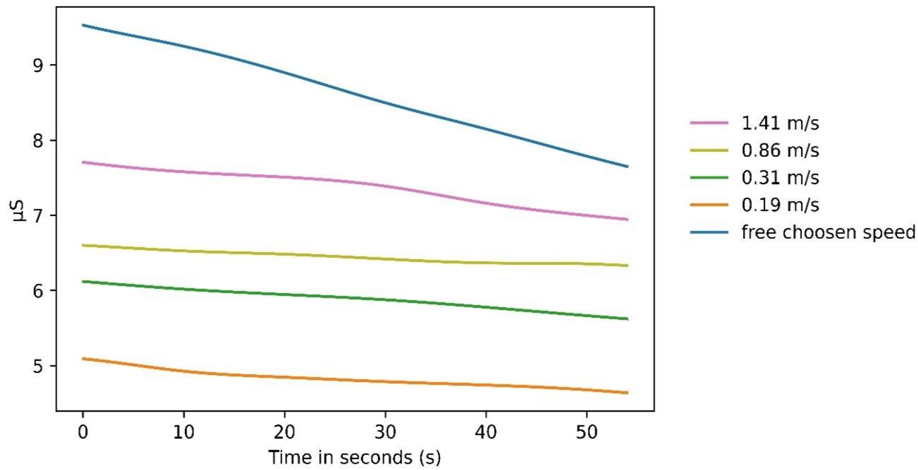


Figure 22: Average SCL scores over time across all subjects for freely chosen walking speed.

The NS.SCR also differed significantly between the free-choice velocity and slow conditions (Friedman test: X^2 (4) = 26.02, p < .001). Looking at the EDA Symp parameter, we found a significant difference between the "freely chosen walking speed" condition and the given mean slow condition of 0.31 m/s (Friedman test: X^2 (4) = 20.61.17, p <.001). Significant differences were not found between any other conditions in the NS.SCR comparisons.

Table 13: Post-hoc comparisons: significant differences in the EDA parameters for freely chosen walking speed.

Comparison	SCL	EDA Symp	Mean SCR Amplitude
Freely chosen speed – 0.89 m/s	p = .007	p = .015	p = .006
Freely chosen speed – 0.31 m/s	p = .006		
Freely chosen speed – 0.19 m/s	p = .005		p = .05
1.41 m/s – 0.31 m/s	p = .033		
1.41 m/s – 0.19 m/s	p = .003		p = .05

Table 14: Means and standard deviations (in brackets) for all conditions for the first 54 seconds, comparing the preset speed values to the freely chosen speed values.

Condition	SCL	EDA Symp	Mean SCR Amplitude	NS.SCR
Freely chosen Speed	8.54 µS (3.91 µS)	.038 (.048)	.0022 µS (.0021 µS)	8.41 (3.20)
1.41 m/s	7.31 µS (3.58 µS)	.02 (.027)	.0016 µS (.0017 µS)	9.06 (2.36)
0.86 m/s	6.43 µS (2.91 µS)	.01 (.016)	.00074 µS (.00066 µS)	8.06 (3.21)
0.31 m/s	5.87 µS (3.12 µS)	.015 (.027)	.00073 µS (.00095 µS)	7.53 (1.97)
0.19 m/s	4.81 µS (3.42 µS)	.0098 (.018)	.014 µS (.001 µS)	7.47 (3.00)

In addition to comparing the freely selected walking speed with the externally imposed walking speeds, the externally imposed walking speed times were also compared. The quantitative analysis revealed that the averaged SCL values decreased over time for all the walking speed conditions (Figure 23); the slopes in the graph do not intersect or show different excitation levels, but it should be noted that the faster the subjects walked, the higher their stress values. This was also evident when quantitatively examining the parameters. Here, significant differences in SCL values were found (Friedman test: X^2 (3) = 29.54, $p < .001$) (Tables 15 and 16). The NS.SCRs also differed significantly (Friedman test: X^2 (3) = 15.54, $p < .002$). Sympathetic activation measured by the parameter EDA Symp was significantly different between the conditions (Friedman test: X^2 (3) = 14.51, $p = .014$). The last two comparisons showed no significant difference in the post-hoc tests.

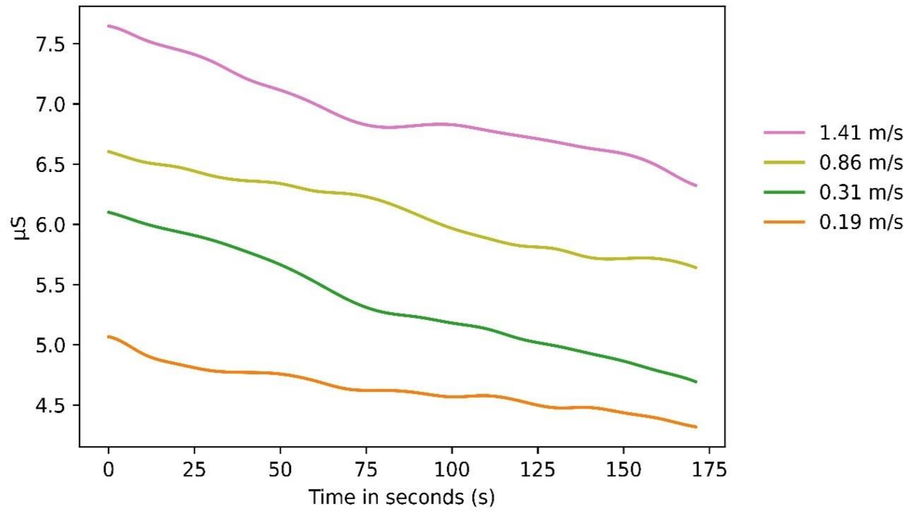


Figure 23: Averaged SCL scores across all subjects over the experimental run times of 3 minutes per condition.

Table 15: Post-hoc comparisons: significant differences between conditions for the EDA parameters over the experimental run time 3 minutes per condition.

Comparison	SCL
1.41 m/s – 0.86 m/s	p = .007
1.41 m/s – 0.31 m/s	p = .002
1.41 m/s – 0.19 m/s	p = .005

Table 16: Means and standard deviations (in brackets) for all conditions and all EDA parameters over the experimental run times of 3 minutes per condition.

Condition	SCL	EDA Symp	Mean SCR Amplitude	NS.SCR
1.41 m/s	6.91 µS (3.1 µS)	.023 (.026)	.0013 µS (.0013 µS)	24.47 (10.54)
0.86 m/s	6.08 µS (2.68 µS)	.013 (.021)	.00067 µS (.0007 µS)	25.12 (11.45)
0.31 m/s	5.33 µS (3.05 µS)	.018 (.032)	.00073 µS (.00095 µS)	27.65 (12.59)
0.19 m/s	4.62 µS (3.32 µS)	.016 (.024)	.0065 µS (.00091 µS)	26.24 (10.87)

6.1.3.3 Influence of habitual walking speed and the desire to overtake

The influence of the person’s typical walking speed on their desire to overtake others was investigated statistically using a mixed model. The standardized EDA data ensured a direct comparison between the groups. However, neither the freely chosen speed nor the desire to overtake had a mediating influence on the EDA parameters.

6.1.4 Discussion

The results of the study are interesting in two respects. First, the comparisons of the varying walking speeds show that fast walking is associated with increased stress levels. This was evident for several parameters. Although this effect was contrary to our hypothesis, the activation of the sympathetic nervous system due to physical activity can explain the increased response. For example, Posada-Quintero and colleagues (2018) showed in an exercise study that walking at increased speeds on a treadmill is associated with increased sympathetic activity and thus higher EDA levels. However, the assumption that subjects perceived changes in walking speed from the natural gait to low walking speeds as more difficult and unpleasant was not confirmed in this study. Nevertheless, the questionnaire results include statements such as “Because it was much slower than I was used to and I had a hard time coordinating my body (legs and feet),” which support the idea that an increase in cognitive effort is required to maintain balance. Nevertheless, the results indicated that this effort affected stress levels and sympathetic nervous system activity less than physical activation did in the fast conditions.

Furthermore, a freely chosen speed of 1.39 m/s on average was more arousing than walking behind the experimenter according to externally imposed speeds. These results were not only evident in the qualitative assessments, but also the quantitative comparisons. A possible explanation for this higher state of arousal is that higher cognitive load is associated with walking alone at free speed when engaging in activities such as way-finding and orientation, whereas these cognitive processes are not needed while following a person. Two studies by Armougum et al. (2020; 2019) showed increased physiological responses when using cognitive processes in real-life travel and virtual reality travel contexts. Another explanation is that the subjects walking alone might have felt more insecure about whether they were performing the experiment "correctly" or might have felt observed by the experimenter.

This study is limited by the fact that it was a pure laboratory study, and the results cannot be transferred to a one-to-one real life. For example, the individuals in the study were not intrinsically motivated to be fast and did not have the deadline pressures of real-life situations. Nevertheless, the study provides some insight into the physiology of walking and allows for further studies to add other parameters, such as motivation or deadline pressure, to investigate the impact of other internal and external stressors.

Overall, the results of this study indicate that freely chosen walking speed alone does not result in a low-stress experience in crowds. Rather, it should be considered that freely choosing a walking speed involves cognitive and social processes that may lead to increased arousal states (Armougum et al., 2019). Therefore, it may be more pleasant to walk in a stream of people with an adapted walking speed and the same spatial destination than to find one's own way. In addition, and most importantly, it was shown here that physical exertion had a significant effect on skin conductance. This must be considered in further studies that involve walking.

All these results were interpreted within a context whereby the distance to the person in front was kept constant, and thus personal space violation did not need to be considered as an influencing variable. The PLOS, however, as explained above, includes this information. To systematically consider the influence of the violation of personal space, therefore, we carried out a second motion study (Study 4). For this purpose, we reduced the walking speed by increasing density and then measured the stress parameters.

6.2 Walking Speed and Density: Study 4

6.2.1 Hypothesis

1. The slower the subjects walk because of increasing density, the more stressed they will be, and the higher their SC values will be.

6.2.2 Materials and Methods

6.2.2.1 Subjects

Study 4 was conducted as part of a series of large-scale experiments on pedestrian dynamics in the CroMa Project. For more detailed information about the conducted sub-experiments see Boomers et al. (2023). For the study, 80 people were selected. The subjects had to be younger than 35 years old and neurologically and psychologically healthy; this information was collected using a self-report questionnaire. The intended gender distribution was 50% male, 50% female. Of the 80 experimental subjects, 56 were fitted with sensors for measuring physiological arousal. After checking the EDA signals for artifacts such as null lines or extreme fluctuations due to motion or contact problems with the electrodes, or incomplete data sets for each experimental condition, I excluded 12 subjects from further analysis. The mean age of the 44 subjects included in the final analysis was 26 years (+/- 4). The final gender distribution was 20 (45.5%) females and 24 (54.5 %) males. The genders were evenly distributed in each condition. The methods were in accordance with the Declaration of Helsinki.

6.2.2.2 Procedure and experimental paradigm

The study took place in the Mitsubishi Electric Hall in Düsseldorf, Germany, in the context of the large-scale CroMa Project experiments. Informed consent was obtained at the beginning of the experiments. The subjects could refuse to participate in individual experiments after being informed about the procedure of the experiment. The Ethics Council of the DGPs approved the experiments. The experiment set up was a classical single-file experiment (Seyfried et al., 2005). Two ovals were glued to the floor, the circumference was 14.97 m for both with a walking width of 0.8 m (Figure 24, for further information see Boomers et al. (2023)).

Figure 24: Camera snapshot of the Study 4 experiment setup and the execution of the experimental conditions: 24 and 16 persons per oval.

The ovals were separated from each other with a wooden wall. There were eight experimental conditions. The different conditions are given in Table 17, together with the area available to each subject, excluding their body size. Each subject went through each experimental condition, but not necessarily in the same order. Also shown is the amount of space between subjects when the subjects were evenly spaced. For this purpose, the average body depth of 28.8 cm according to Buchmüller and Weidmann (2006) was subtracted from the available area (Table 17).

Table 17: Experimental runs, which the subjects went through at least once.

Experimental condition's name	Number of persons in the oval	Space for each person in meters	Space for each person after subtracting the depth of the human body in meters	Social distance zones, taken from Hall (1966)
Oval 4	4	3.74	3.45	Social far
Oval 8	8	1.87	1.58	Social near
Oval 16	16	0.94	0.65	Personal near
Oval 20	20	0.75	0.46	Personal near
Oval 24	24	0.62	0.33	Intimate far
Oval 32	32	0.47	0.18	Intimate far
Oval 36	36	0.42	0.13	Intimate near
Oval 40	40	0.37	0.08	Intimate near

6.2.2.3 Statistical analysis

Possible significant differences between the different experimental conditions were tested using one-way analysis of variance (ANOVA) with repeated measures. The parameters that were compared were EDA Symp, SCL, Mean SCR Amplitude, and NS.SCR level (see Chapter 3). The conditions were collected at different time intervals. The shortest interval was used as a basis for the comparisons, and then the corresponding EDA parameters for a given time period were determined.

For the ANOVA tests, normal distribution was checked using the Kolmorov-Smirnov test. Then the individual conditions were tested using post-hoc t-tests, applying the Bonferroni method for multiple testing. Where the assumption of sphericity was violated, the Greenhouse-Geisser correction was used.

6.2.3 Results

6.2.3.1 Results: Skin Conductance (SC)

Looking at the SCL data over time, it was noticeable that there was a pattern in the different conditions. The slopes for the conditions Oval 4 and Oval 8 were closer together and demonstrate the least stress. This is also true for the conditions Oval 36 and Oval 40. The slopes for the conditions Oval 16, Oval 20, Oval 24, and Oval 32 are unsorted and close to each other in the middle range (see Figure 25). In addition, there was an adaptation phase in which all the slopes fall very clearly (0–20s). After this, the slopes fall only slightly and a few even rise again.

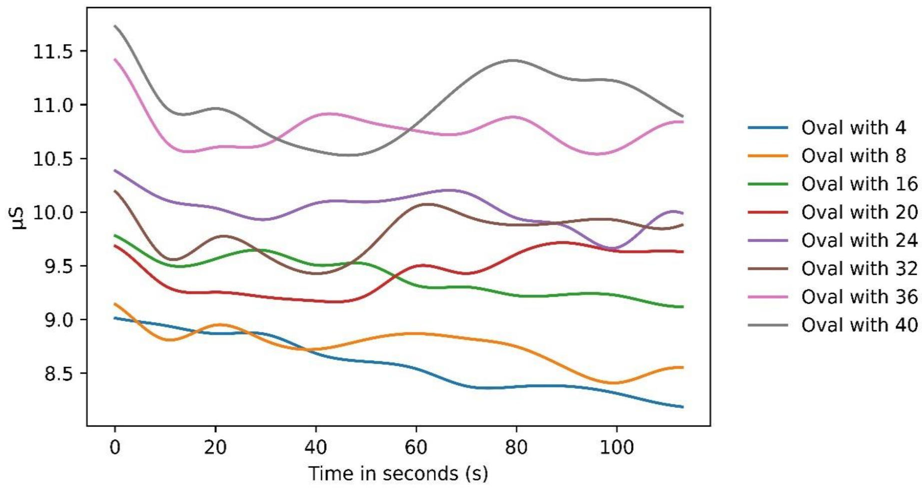


Figure 25: Averaged SCL scores over time across all subjects for all density conditions.

Furthermore, looking at the distribution, the SCL increases as the density increases (Figure 25). The quantitative analysis shows that several significant differences ($F(3.88, 166.70) = 10.73$, $p < .001$, Greenhouse-Geisser corrected) emerged for SCL (see Tables 19 and 20).

The significant differences in the EDA parameters are given in Table 18. Amplitude showed some significant differences between the conditions ($F(3.99, 171.48) = 9.14$, $p < .001$, Greenhouse-Geisser corrected), the sympathetic activation parameter (EDA Symp) had significantly higher values ($F(4.09, 175.84) = 3.76$, $p = .006$, Greenhouse-Geisser corrected), and the NS.SCR comparisons were also significantly different ($F(4.32, 185.67) = 2.49$, $p = .041$, Greenhouse-Geisser corrected). The means and standard deviations for the conditions are given in Table 19.

Table 18: Post-hoc comparisons: significant differences for the EDA parameters.

Comparison	SCL	EDA Symp	Mean SCR Amplitude	NS.SCR
4 Subjects – 24 Subjects	p = .033			
4 Subjects – 32 Subjects			p = .005	
4 Subjects – 36 Subjects	p = .001	p = .032	p < .001	
4 Subjects – 40 Subjects	p < .001		p = .003	
8 Subjects – 32 Subjects			p = .034	
8 Subjects – 36 Subjects	p < .001		p = .001	p = .012
8 Subjects – 40 Subjects	p < .001		p = .020	p = .026
16 Subjects – 32 Subjects			p = .040	
16 Subjects – 36 Subjects	p = .023		p = .007	
16 Subjects – 40 Subjects	p = .019			
20 Subjects – 36 Subjects	p = .008		p = .003	
20 Subjects – 40 Subjects	p = .010			
32 Subjects – 36 Subjects	p = .023			
32 Subjects – 40 Subjects	p = .048			

Table 19: Means and standard deviations (in brackets) for all conditions.

Condition	SCL	EDA Symp	Mean SCR Amplitude	NS.SCR
4 Subjects	8.58 µS (3.87 µS)	.04 (.07)	.0015 µS (.0012 µS)	18.14 (6.9)
8 Subjects	8.77 µS (4.39 µS)	.07 (.14)	.0017 µS (.0018 µS)	16.52 (6.26)
16 Subjects	9.35 µS (5.00 µS)	.05 (.06)	.0018 µS (.0018 µS)	16.66 (7.54)
20 Subjects	9.3 µS (5.29 µS)	.1 (.25)	.0020 µS (.0020 µS)	17.91 (9.69)
24 Subjects	9.95 µS (5.33 µS)	.11 (.2)	.0024 µS (.0027 µS)	18.43 (8.29)
32 Subjects	9.72 µS (5.05 µS)	.13 (.22)	.0027 µS (.0025 µS)	17.48 (7.09)
36 Subjects	10.71 µS (4.98 µS)	.17 (.26)	.0032 µS (.0027 µS)	19.5 (6.4)
40 Subjects	10.9 µS (4.93 µS)	.19 (.35)	.0032 µS (.0031 µS)	19.7 (6.7)

6.2.4 Discussion

Study 4 showed that density had a significant effect on sympathetic nervous system arousal while walking. The different EDA parameters (SCL, EDA Symp, amplitude) showed an increase in stress with increasing density. Research indicates that a violation of personal space is associated with increased stress levels. However, in contrast, I considered personal space in more differentiated graduations and found differences related to the individual distance zones. The degree to which the ovals were filled in the study was assigned to different distance zones (see Table 18 above) based on the space available in the individual conditions. Thus, the 4-person condition corresponded to the far social distance zone and the 8-person condition corresponded to the near social distance zone. The conditions with 16 and 20 persons were assigned to the personal near distance zone. The conditions with 24 and 32 persons were assigned to the intimate far distance zone. The conditions with 36 and 40 persons were assigned to the intimate close distance zone.

The results of the study showed that the social far distance zone and personal near distance zone led to less stress than the intimate near distance zone. The personal far condition zone was not examined in this study but, based on the results collected, it would probably also differ from the intimate near zone conditions. Overall, it appears that reduced space leads to more stress, and this then leads to an increase in EDA stress parameters.

When looking at the graph slopes for the 4- and 8-person conditions, it is noticeable that they are close to each other. Although they belong to the same distance zone, there is a difference in available space between them, and they are in different subcategories: one is close and the other is far. However, the lack of difference between the 4- and 8-person conditions demonstrated how big the difference was between these zones and the others in terms of stress level. It can be concluded that the social distance zone does not generate a higher level of stress compared to the other zones. Furthermore, there were no significant differences within these individual distance zones. This calls into question the distinction between near and far zones in walking in terms of the stress level triggered. Further studies are needed to obtain a more comprehensive picture of this issue.

This study offers an unsurprising observation—that moving in a confined space leads to increased stress experience. Unlike the studies 1 and 2, which found no correlation between stress experience and waiting in dense situations, the results here indicate that increased density and thus a reduced amount of space leads to increased stress levels in moving people. One possible explanation for this arises from the additional cognitive effort required when moving. Slow walking requires more attention when trying not to touch the person in front of you and having to match their rhythm. Furthermore, walking in a very dense crowd always carries the risk of pressure, being hurt, or hurting someone else, while the risk of sudden pressure is very low in studies with stationary settings like the Tiny Box experiment.

The results of Study 4 are also consistent with the assumption that the quality of walking for pedestrians decreases as density increases. Thus, this very reduced-scale experiment is sufficient to show that changes in distance to people in front and behind influence stress scores. Not considered was the presence of people to the left and right while walking, which would further increase density. Moreover, it remains open in this experiment as to what influence Weidmann's (1993) criteria, such as speed change and reaching one's destination, have on stress levels. It would also have been interesting to measure subjective perceptions after each experimental condition to compare subjective values with objective values. Furthermore, investigations of whether smaller densities lead to violations of the distance range "personal far" should be looked at, as unfortunately, they were not considered in this study.

6.3 Conclusion: Studies 3 and 4

The two motion studies (Studies 3 and 4) complement each other: while in Study 3 arousal was higher with faster walking, the opposite was the case in Study 4. From our point of view, this underlines the strong influence of stress due to increased density and proximity in Study 4; considering that slower walking requires lower body activation, it is significant that slower walking in high-density environments leads to higher arousal than faster walking in low-density ones. The combination of Studies 3 and 4 allows us to distinguish between the effects of walking speed per se and walking speed due to density.

The results of these two studies clearly demonstrate the influence of a) personal space violation and b) speed on stress levels while walking. Thus, they provide a better understanding of the stress experiences of people in crowds. Contrary to situations in which people are waiting, when people walk, density matters. Increased density (decreased personal space) goes along with higher arousal. Furthermore, from a methodological perspective, Studies 3 and 4 enhance our understanding of the physiology of walking and its influence on EDA. Walking speed indeed increases arousal, as measured by EDA. This needs to be considered when interpreting EDA data in walking experiments. This was rather easy in the case of Study 4 because the results were in the opposite direction slower walking leads to increased EDA Values and therefore could be interpreted as an effect of stress. The experiments thus show that EDA is a good method for studying sympathetic arousal in pedestrian dynamics research. The method opens numerous possibilities for future studies to achieve a better understanding of how people feel in crowds and which factors lower the quality of pedestrian infrastructure.

7 Discussion

This thesis addresses two main topics. The first is the effect of experiencing density, speed, and the interaction of the two parameters on the psychological stress experience of individuals. The second is the use of EDA as a method for measuring the individual stress experience in crowds. This chapter first reviews the results of the studies presented in Chapter 5 and 6 and examine them considering the theories presented in Chapter 2. Then it discusses the usefulness of using EDA as an indicator of stress in experimental designs. The end of this chapter presents suggestions for further research.

7.1 Waiting vs. Walking

The studies presented in Chapter 5 and 6 used laboratory experimental designs to investigate the different states of pedestrians in public transport situations (stationary waiting and moving) and their associated arousal. The main research focus was to analyze the relationships between density situations and the stress experiences of persons in pedestrian situations. This thesis examined two classic pedestrian situations—waiting in crowds and walking in streams of pedestrians—. Previous scientific work on this topic has shown that valid observation of persons in such situations is quite difficult, especially when considering their stress levels under real-life conditions. Accordingly, the focus was on learning more about the theoretical relations and using EDA as an indicator of arousal, using a more controllable laboratory experimental design, although it is recognized that in this type of experimental design, subjects may be influenced by specific expectancies.

Compared to field studies, laboratory experiments offer the advantage of more standardized situations and potential influencing factors can be controlled. But it must be acknowledged that not all unintended interactions between the participating persons and the environment can be controlled, especially when it is necessary for several persons to participate in an experiment at the same time. However, having a fixed script for the procedures and filming the experiments provides more overall control. This also allows a checkup for results, which do not fit in the hypotheses to be sure that nothing strange happened during the experiment. So, confounding influences can be accounted for in the interpretation. Density influence studies are further characterized by an accurate specification of the density condition experienced by the subjects. This applies in the same way when exploring the influence of speed. With respect to walking, treadmill studies have a high level of control concerning speed. However, they are characterized by a substantial disadvantage related to the impact on cognitive demands. Conducting real-life walking studies rather than using a treadmill has the advantage that the unfamiliar treadmill walking task cannot influence the data.

Studies 1 and 2 dealt with the influence of stationary density on arousal. In accordance with the research question, the Tiny Box experiment was chosen to observe stress levels. Study 2 showed that people perceived higher densities subjectively as more unpleasant. However, the EDA arousal parameter results in Study 1 and 2 showed that the influence of high densities in stationary situations is highly dependent on factors in the environment and social interaction. In his model, Vine (1982) integrated other factors into the development of crowding stress to fit the results. In addition to personality factors and individual motivations, such as deadlines and time pressures, environmental factors were also considered in Vine's (1982) model. For a better differentiation of these influencing factors, further studies are necessary, especially those that consider the influence of various environmental factors or the motivations of individuals at constant density. That is not possible using the Tiny Box experimental design. To improve external validity, it is important to ensure that in situations where many people are waiting, such as before a concert, potentially stressful influencing factors are quickly identified, so that further crowding and dangerous situations can be avoided.

The interpretation of these results is limited because there was no adequate consideration of personal space. Ultimately, it remains to be considered whether crowded locations are almost always confounded with violations of the intimate zone of personal space. To achieve a more differentiated picture here, it is necessary to use even larger areas in the experiments to investigate the systematic influence of the violation of personal space on waiting individuals. However, a simple transformation of these experimental designs into larger spatial contexts is not useful based on the available findings. In larger spaces, subjects might be expected to seek an equal distance between those standing around (Konya & Sieben, 2023; Küpper & Seyfried, in progress). Furthermore, even when in the Tiny Box experimental setup, there is only one person per m^2 and the personal distance is violated only by the walls of the box, the stress values are comparable to those in Densities 6 and 8 and can be attributed to the peculiarity of the situation where one is alone in the box. Nevertheless, the influence of violations of personal space by objects, such as walls or other objects, should also be considered in further studies. Based on the assumption described in the literature—that communicating with other persons in a density situation can lead to stress reduction—some of the subjects in Studies 1 and 2 were instructed to make verbal contact with the other subjects. However, no reduction in stress was evident in any of the conditions.

Compared to the results of Studies 1 and 2, the results of Study 4 showed that there was a difference between experiencing density in a stationary context and experiencing density in the context of walking at different speeds. The design of Study 4 corresponded to a single-file experiment simulating the values of Weidmann's (1993) fundamental diagram. Study 4 clearly showed that with increasing density and thus decreasing speed, the situation was perceived as more stressful. A possible explanation for this is that executing walking tasks becomes increasingly difficult with increasing density. The disturbance theory supports this explanation (see Section 2.2.3.2), which states that interference with the execution of a task, which in the context of this research is walking, leads to increased crowding stress. The higher stress levels show up even when it is perceived that the disruption of the task by others was without malicious intent. Therefore, there may be fewer aversive reactions in real life than when the task disruption is assumed to be intentional, as in experimental studies (Stokols, 1978). Furthermore, violation of personal space seems to play a role, because if only task disruption led to higher stress values, the results of Studies 3 and Study 4 would point in the same direction. Both studies restricted the ability to freely choose walking speed, but only in Study 4 was the restriction of speed a consequence of density and violation of personal space. To achieve a more comprehensive picture of the influence of personal space, further studies should be conducted. These should include studies where another pedestrian violates the personal space and studies in which obstacles, such as bottlenecks, reduced the space and speed.

Overall, the results of the studies presented here support the usefulness of the experimental approach for linking the convenience of transportation facilities to the context of density. Moreover, the results support Fruin's (1987) existing understanding of the distinction between a PLOS for motion and one for waiting. The CroMa Project also pursued the development of a PLOS for waiting at platforms. However, the assumption of density as the main influence parameter was abandoned and criteria such as free choice of the waiting place or keeping a personal distance of around 1 m were included. However, these criteria indirectly influence density. In the future, therefore, environmental parameters and personal motivations should be included in the investigation.

7.2 Short vs. Long time spans in the Experimental Designs

The results presented here refer to a relatively long exposure time in a density situation. In daily life, we experience situations like this in the context of movement in crowds in queues, on trains, and in elevators, for example. In everyday life, there are also many other situations in which personal space and task performance are violated, as a study by Engelniederhammer et al. (2019) shows. This often involves brief violations of personal space by people crossing the path of or passing very close to "waiting" people. Exploring such momentary violations is very complex due to the slow response of EDA to stimuli, and can be best done using targeted investigations; for example, Zhao et al. (2019) always made subjects wait 10 seconds before having individual contact with other people and thus achieved an accurate relationship between EDA response and injury to personal space.

Also in the CroMa Project, an attempt was made to investigate the short-term violation of personal space by people waiting (Boomers et al., 2023). A rectangle with an area of 64.13 m^2 was created, in which seven people were positioned to wait. Then 10 people had the task of walking past the subjects at different distances. Unfortunately, the control of this experimental design turned out to be quite difficult. The experiment had two weaknesses: First, too many people often walked past the waiting subjects at the same time, so an accurate attribution of responses to the stimuli could not be made (Figure 26). Second, some of the subjects who pass by showed distracting behaviors and gestures, such as walking in circles around the waiting subjects or walking backward past them. These problems created a significant amount of unusable data and show how complex and difficult it is to collect data on factors influencing crowding stress, even with advanced measurement methods. Currently, the existing state of knowledge and the realization of potential experimental designs makes it necessary to focus on experimental designs like the Tiny Box or the Oval. They allow us to get a picture of the experience of stress and help to further develop research paradigms. Nevertheless, the study of short-term violations is also important. In addition, experiments such as that of Zhao et al. (2019) must be implemented to gain a basic understanding of the influence of short-term violations on subjects by other persons or objects.

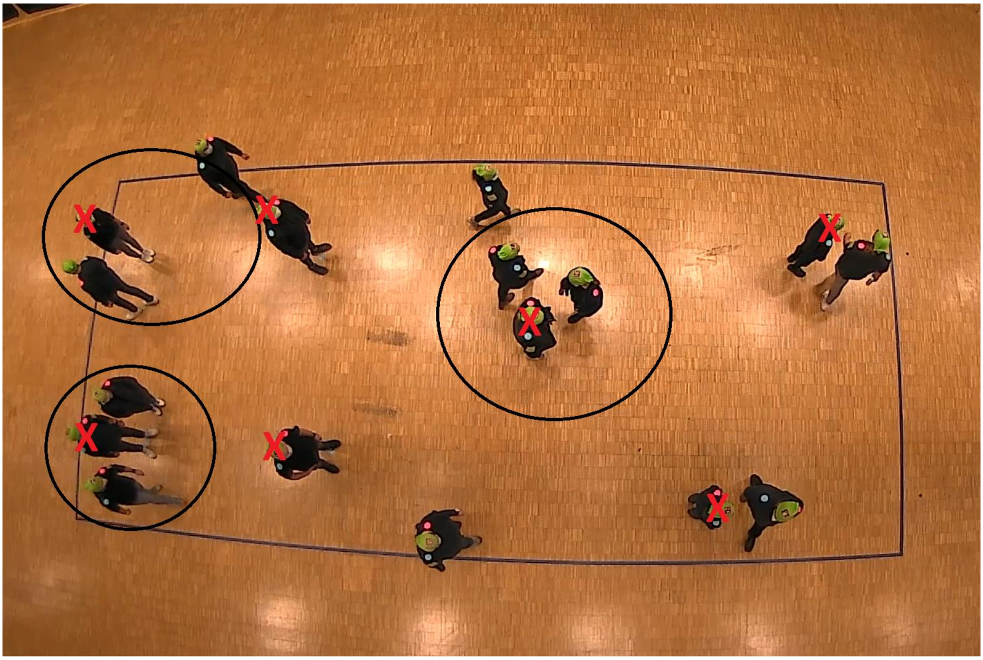


Figure 26: Camera snapshot of the short-term violation of personal space experiment. The red X marks the standing subjects. The black circles mark the problematic situations.

7.3 EDA as a Measurement Method

In addition to exploring the impact of density on the arousal of individuals, this work also focused on whether the EDA is a good measure for eliciting physiological arousal in studies involving density and exercise. Overall, it should be noted that EDA as an indicator is not unproblematic in terms of its valid measurement (for more on this, see Chapter 3). For example, physiological measurement methods are often affected by artifacts, especially when investigating motion. Because the EDA signal does not have a uniform course, artifact detection is not easy. Moreover, acquisition by recording a single signal without contextual information requires a good script for valid application in experiments. For application in field experiments, more information about the environment as experienced by the subject is needed to directly associate signals with events. One possibility is trigger-based questionnaires via cell phones, but these always take the subject out of the situation and thus make the situation even more unrealistic. Information can also be obtained from other initial sensors integrated into the EDA sensor, such as accelerometers or antegular sensors. This information can also be used for artifact detection, as described in Chapter 3. Problems with signal recording and electrode contact always lead to loss of data and in some cases, to the exclusion of subjects. Therefore, when designing EDA studies, enough subjects should always be recruited to obtain valid results. An advantage of the EDA method is the manageable number of parameters that can be collected and the good distinction between tonic and phasic parameters. Moreover, the use of averages across all subjects at each time point reduces the loss of information compared to looking at averages across the entire time period. The studies in this thesis have shown that EDA provides differentiable results between conditions, both in the waiting state and walking, and can depict a change in arousal as a function of the condition. Nevertheless, alternatives to EDA should also be considered, such as heart rate measurement.

7.3.1 Alternative to EDA: Heart rate variability

Another method widely used in psychology to study arousal and stress is the observation of heart activity. Unlike the sweat glands of the skin, the heart's action is modulated by both the sympathetic and parasympathetic nervous systems. The sympathetic nervous system takes on the activating role, while the parasympathetic nervous system has a down-regulating part (Gramann & Schandry, 2009). The main task of the heart is to transport oxygen and other energy-giving substances to the organs to maintain the body's functions.

Overall, in psychological research heart rate (HR) is often used to answer questions concerning the resting state (Pham et al., 2021). In the context of stress, only parameters related to the sympathetic nervous system are considered (Posada-Quintero et al., 2019). In the analysis of cardiac activity, a distinction is made between time-dependent and frequency-dependent analyses (Pham et al., 2021). Time-dependent parameters include the pulse, which is determined by the number of Rs in a given time range, and the heart rate variability (HRV), which is determined by the variance of the distances between the R spikes. In this case, the shorter the distance between the R-R spikes, the higher the arousal. One of the frequency-dependent parameters is the heart rate variability low frequency (HRVLF). This is the spectral analysis of the parameter HRV, and is also the parameter on which the EDA Symp parameter is based (Posada-Quintero et al., 2016). The frequency range of interest here is [0.045 to 0.15 Hz] (Posada-Quintero et al., 2019). For a detailed overview of all HR parameters, the paper by Pham et al. (2021) is recommended. Unlike EDA with the SCR, HR does not have an explicit phasic component. To examine responses to specific stimuli, HRV is considered in a fixed time period between 1 to 15 seconds after the onset of the stimulus; thus, HR is a parameter that responds faster to stimuli than EDA.

Nevertheless, some problems accompanied the use of HR. Just as with the EDA method, it takes a good script or recording of the experiments to be able to track exactly what people are responding to and establish context. In addition, although the regular signal makes artifact detection much easier, it can also be algorithm driven. Studies that use heart rate sensors also often show high subject dropout due to highly artifact-laden data. For example, the HR sensors used in Studies 2, 3, and 4 of this thesis resulted in a loss of more than 50% of the test subjects. This may have been due, among other things, to the positioning of the sensors under the T-shirts, sweaters, and jackets during the trials in real-life situations. In addition, HR is a measurement method that is highly susceptible to physical arousal or physical exertion (Lee et al., 2020). Nevertheless, HR is popularly used in travel research to study the stress experience of cyclists, although, in such research, EDA is not an option because the hands are used when riding a bicycle.

7.4 Conclusion and Outlook

The presented work shows the usefulness of the cooperation between engineering science and psychology in the context of pedestrian research. For this purpose, the interlocking theoretical foundations of the two disciplines in relation to crowding are presented in Chapter 2 of this thesis. To take advantage of the complementary perspectives between the two disciplines, this thesis employed psychology and EDA methods and questionnaires, while at the same time, experimental designs from pedestrian research, such as the single-file experiment, were used to investigate the relationships between density, speed, and the experience of the context. In addition, suggestions for new exploratory experiments are presented that will further examine the relationships between desired walking speed and stress and between waiting in high densities and stress. In doing this, using the comparatively large samples that are common in pedestrian research and several types of sensors will allow the study of these relationships to be efficient and economical.

The results presented here show how complex the relationship between stress and density is and that, empirically, this field of research is still in its infancy. However, using the EDA method shows that technical progress has made it possible to conduct investigations, especially large laboratory experiments, on the experience of stress in density in different pedestrian conditions (walking and standing/waiting). This means we can extend and improve existing concepts such as the PLOS, particularly in the assessment of pedestrian comfort. Furthermore, the results of this work suggest that distinguishing between a PLOS for walking people, and a PLOS for people who are waiting, would be very useful. A PLOS for train platforms has already been developed as part of the CroMa Project, which includes a section for the evaluation of long and short waiting. Free choice of waiting place and keeping a personal distance of approximately 1 m were also evaluated within the criteria. The results from Studies 1 and 2 presented here suggest that other factors besides density, such as acoustics or mood in the surrounding environment, influence stress while waiting.

Therefore, these aspects should be specifically investigated in the future and integrated into the PLOS for waiting at the train platform or more generally into Fruin's (1987) PLOS for waiting areas.

Unquestionably, conducting field observations would be important and interesting in the future. However, as mentioned above, this type of research requires good scripts that capture what the person has experienced. In the context of train stations, for example, this could be realized by using platforms equipped with trajectory cameras, such as those at Frankfurt HBF train station in Germany. Nevertheless, such experiments require high logistical effort and the cameras do not capture all the information about the situation on the platform. Other relevant environmental information would need to be collected, such as sounds or the atmosphere. Furthermore, through this research, it became apparent that it does not make sense to analyze density situations without interviewing the subjects. This will help us to understand to what the test subjects attribute the high level of their arousal and whether they perceive violations as only unpleasant or as threatening. These are important directions for the design of environmental studies.

This field of research is still in its infancy, and using psychological theories and physiological methods can give us a better understanding of what people experience when in crowds. But only further research, in which engineering science, physics, and psychology disciplines work together, will allow for a more comprehensive understanding and integration of existing concepts and the implementation of approaches that make it easier and safer for people to experience crowds daily, whether it be at the train station, in the shopping mall, or at festivals or large events.

8 References

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9 Contributions

Contribution in chapters 5 and 6:

Conceptualization: Mira Beermann and Anna Sieben

Data curation: Mira Beermann

Formal analysis: Mira Beermann

Investigation: Mira Beermann

Methodology: Mira Beermann

Project administration: Mira Beermann

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Supervision: Anna Sieben

Validation: Mira Beermann

Visualization: Mira Beermann

Writing: Mira Beermann

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Investigation: Mira Beermann

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Language support: DeepL

Lebenslauf

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