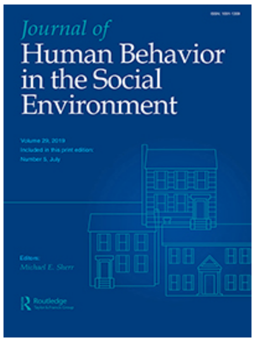

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Crowding density in urban environment and its effects on emotional responding of pedestrians: Using wearable device technology with sensors capturing proximity and psychophysiological emotion responses while walking in the street

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ABSTRACT

We conducted a study to examine the influence of crowding in high-density urban areas on the emotional responses of people. We hypothesized that high density leads to the invasion of a personal space that is surrounding everyone's body which in turn evokes emotional responses, especially negative emotions like stress and aggression. Subjects (n = 30) walked a predefined, crowded path in a Hong Kong commercial center which consisted of urban parts and a park. Along the way, emotional responses were measured psychophysiologically via a wearable device, capturing electrodermal activity, skin temperature, and ambient temperature, among others. Additionally, we used a movement detection sensor to measure the invasion of personal space by other pedestrians. Significant effects of personal space crossings on aversive and appetitive emotional responses are found. Implications for future research are discussed.

KEYWORDS

Emotion; psychophysiology; crowding; personal space

Introduction

Worldwide urbanization in many areas leads to very high-density urban living conditions, for example, in Hong Kong, there are about 40,000 people per km^2 (Berlin: 4000 p/km^2). Beside other factors of urban infrastructure, pollution, transportation congestion, etc., high urban population density feeds in an urban environment which is characterized by a high pedestrian density. Peen, Schoevers, Beekman, and Dekker (2010) show that mood and anxiety disorders are more prevalent in urban than in rural areas. Furthermore, stress recovery is faster and more complete when people are exposed to videos of natural rather than urban environments (Ulrich et al., 1991). As this might be a pervasive feature of shortening social distance and recurrent invasion to personal space, it seems to be a common risk of high urban density. Besides a high level of socio-spatial complexity and heterogeneity, mental health is impaired by shortening social distance and personal space invasion (Tost, Champagne, & Meyer-Lindenberg, 2015). Cox, Houdmont, and Griffiths (2006) propose a model in which they propose that high density leads to the perception of crowding which evokes an experience of stress. This stressful experience has

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a negative impact on individual and organizational health. As a moderator of the relation between high density and the perception of crowding they propose a lack of control over the situation, i.e., the ability to control the proximity to others.

While the covariation of crowd density and stress load seems quite obvious, only few studies examined this relationship with empirical data on an individual level. Walden and Forsyth (1981) equate crowding with a perception of limited space which is evoked by a situation of high density. In crowded situations, people feel uncomfortable, stressed, tense, annoyed, and frustrated. These reactions are physiologically measurable – crowding relates to decreased skin resistance and increased respiratory rate, cortisol level, blood pressure, and stress-related arousal (Aiello, Nicosia, & Thompson, 1979; Walden & Forsyth, 1981). Aiello et al. (1979) find that children are more competitive, more aggressive and less motivated under high density. The increased aggression might be a result of frustration and competition that occurs when resources are scarce. This is more likely the more people are present.

Personal space

For a deeper understanding of these findings, the concept of personal space is helpful. According to Sommer (1959), personal space is an area with invisible boundaries which surrounds a person's body. Unlike a territory, personal space is not stationary, but rather carried around by each person. Wabnegger, Leutgeb, and Schienle (2016) indicate that personal space might be a phylogenetically acquired trait which has evolved throughout evolutionary history to prevent aggression within and between species or groups. Personal space usually determines interpersonal distance and its effects on psychophysiological responses to varying distances.

In his Proxemic Theory, Hall (1966) divides interpersonal distance into four different zones: intimate, personal, social and public distance (each with close and far phases). People seek to maintain these distances from others to prevent unsolicited touch by strangers (Vine, 1982). Entering somebody's personal space is usually a sign of familiarity or intimacy.

However, in urban high-density living conditions, maintaining everybody's personal space can prove difficult, for example, when walking in high-density streets. This physical proximity and intrusion into personal space (especially the personal or intimate distance) by strangers are experienced as being uncomfortable and disturbing by many people. When somebody intrudes into someone else's personal space, the results are anxiety, stress, flight, aggression, and negative mood (Allekian, 1973; Altman, 1975; Efran & Cheyne, 1974; Kanaga & Flynn, 1981; Smith & Knowles, 1978).

Wollman, Kelly, and Bordens (1994) show that, in the work context, personal space invasion evokes less negative reactions when one's territory is frequently intruded and therefore one is prepared for the intrusion. Thus, personal space invasions are experienced as less severe in situations where they are expected. Even though one could argue that pedestrians in high-density streets are used to frequent space invasions, the flow of the pedestrians walking towards oneself is not predictable because one assumes that others will respect everyone else's personal space by not approaching too close. Nevertheless, involuntary personal space crossings cannot be avoided, for example, when people draw aside because of other pedestrians' walking behavior. Additionally, research shows negative consequences of personal space intrusions in crowded street situations, too (Hogertz, 2010; Smith & Knowles, 1978).

People in high-density conditions show more withdrawal behaviors than people in low-density conditions, indicating that they feel more intruded under high density because of shorter interpersonal distance (Kaya & Erkip, 1999). Such withdrawal behaviors are a means to protect one's personal space in high-density situations. Examples are nonverbal behaviors like avoiding eye contact, increasing interpersonal distance, and moving or turning away (Demian, 1978; Hall, 1966). Furthermore, subjects are less likely to help someone recover a lost object after this person has been invading their personal space (Konečni, Libuser, Morton, & Ebbesen, 1975), and short distances (i.e., personal space invasion) lead people to cross the street faster and to have more unpleasant, rude, and aggressive impressions of the intruder than long distances (Smith & Knowles, 1978), being also some kind of withdrawal behavior and negative reaction to personal space invasion.

As we conducted our study with Chinese subjects, it is worth mentioning that personal space varies culturally. Cross-cultural studies have found differences in the size of the personal space depending on participants' origin. Beaulieu (2004) compares people from 11 different countries. Anglo Saxons and Asians showed the greatest personal distance among the participants, Latinos the smallest distance, Europeans were in between. Sussman and Rosenfeld's (1982) study yielded similar results, implying that our Chinese participants might react more sensitive to personal space invasion than European or Latino participants would because Chinese categorize an encounter as an intrusion at a larger distance than Europeans or Latinos would.

Biopsychological emotion theory

From this background, it seems reasonable to assume that walking in high-density streets everyday means to experience a trajectory of mostly involuntary intrusions of one's own and others' personal space causing transient stress responses. If assuming that personal space is an evolutionary acquired disposition to respond emotionally when other people are crossing one's ambient space (Wabnegger et al., 2016), it seems necessary to widen the scope of its efficacy by connecting to biopsychological findings of emotional responding. According to biopsychological emotion theory (Ekman, 1992; Izard, 1993; Levenson, 2014; Panksepp, 1982; Panksepp & Watt, 2011), there are separate basic appraisal-reaction sets, which developed as functional systems for survival in an evolutionary process. Even though there is no consensus of how many elementary emotional systems there are (Von Scheve, 2014), fear, anger, sadness, joy, disgust, and curiosity seem to be the core of elementary emotional responses to internal and external stimuli (Turner, Doxa, O'Sullivan, & Penn, 2001).

There is also consensus that the core mechanism evoking emotional response syndromes consists of a non-voluntary, continuous neural appraisal process of internal and external stimulation (Izard, 1993; Lang & Bradley, 2010; LeDoux, 1998; Ortony & Turner, 1990; Scherer, 2001). An emotional response is triggered by the outcome of neuro-affective appraisal processes, with appraisal being an automatic, non-deliberate, non-conscious process (Birbaumer & Jänig, 2010; Zajonc, 1980), by which features of situational stimuli are matched with prototypes like danger, reward expectation, novelty and loss. This neural emotional reaction to stimuli then unfolds on several dimensions, namely as changes in physiological functions, in the muscular-skeletal system (posture, gestures, facial expressions), as well as in motivational tendencies and subjective feelings (Levenson, 2003, 2014).

Hypotheses

Based on the outlined theoretical background, we propose two hypotheses. First, based on the Proxemic Theory by Hall (1966), we assume that involuntary personal space invasions by strangers in high-density street conditions elicit aversive emotions because intrusions into one's personal space are experienced as being uncomfortable (Smith & Knowles, 1978).

H1: Personal space invasions elicit aversive emotional responses.

Personal space crossings may not only be perceived as aversive, but one can imagine that they might also elicit interest or curiosity. This kind of attention on the approach of people is generally appetitive. Therefore, we also test if personal space crossings elicit appetitive emotions.

H2: Person space invasions elicit appetitive emotional responses.

In sum, one can assume that walking and moving in highly crowded streets in high-density urban areas, which means to encounter people by crossing their personal space as well as having them crossed one's own personal space, will elicit emotional responses in real-time. These will presumably be aversive, but maybe also appetitive, as personal space crossing could also elicit responses of curiosity or interest. We will examine this question by applying an unobtrusive wearable sensor technology capturing the flow of personal space intrusions by passive infrared body sensor combined with psychophysiological signal data, by which emotional responses are identified in real-time on a second-by-second resolution.

Data and method

Sample

The subjects (n = 30, age mean = 24.77, age sd = 0.718, 68% female) are Chinese people studying and living in Hong Kong, but no longer than five years. These people are relatively familiar with the Hong Kong living surroundings but would still keep curiosity about the environment. Additionally, they have no heavy mental illness history, no symptomatic systemic sweating (secondary) and no experience of suffering from accident events in the past month.

Design

The study uses a within-subject and between-subject measurement design. Subjects walked a selected route consisting of two parts: the district of Tsim Sha Tsui (a commercial center in Hong Kong with very high pedestrian density) and Kowloon Park. The sample was split into two groups, with one group of subjects starting the route by walking the park path first and then the street part. The other group of subjects walked the same route, but started with the street path, followed by the park path. For this study, we only used the city walk data because we are interested in the influence of urban high-density street conditions on emotional responses.

All subjects came to a predefined meeting point, where body sensors were attached. Prior to the walk, they went through a smartphone app with specific tests and questionnaires. After the first route part (park path or street path, respectively), they returned to the meeting point and went through the smartphone app again. After the second part of the total route, they again returned to the meeting point, where they went through the app questionnaire a third time.

At selected predefined spots, subjects were told to orient themselves in a specific direction and answer several questions in the smartphone app about their subjective evaluation of the visible environment. In the end, socio-demographic information and general urban attitudes were collected. For the city street part of the route at the four corners indicating the beginning of each street path, subjects were asked to suspend walking to experience the coming streetscape for 10 s and answer the app questionnaire.

Walking path

The predefined urban street walking path (Figure 1) is adjacent to Tsim Sha Tsui, a commercial center in Hong Kong. In addition to a big shopping mall, there are lots of retails, restaurants and exhibition areas. Its pedestrian volume is huge every day.

The urban street path encompasses four roads: Nathan Rd (street path 1), Peking Rd (street path 2), Hankow Rd (street path 3) and Haiphong Rd (street path 4). Nathan Rd is a main city road with four lanes separated by central isolation greening zone. Peking Rd has two lanes in the same direction without greening on any side. An entrance to a shopping mall is on the right side of Peking Rd, which forms a big public space. The width of Hankow Rd is equal to two lanes, but one of them is used for parking, and the other side is planted with street trees. Haiphong Rd is located between the city part and the human-made park, where one observes old and tall trees.

Data were collected during April 2017. On each experimental day, two to four subjects were asked to experience the predefined city walking path around mid-noon separately. The instructor gave the basic experimental introduction to the subjects at the meeting point which is near the human-made park.

Psychophysiological signals and emotional responses

In this study, we used a sensor device to measure emotional responses. This smart-band (Figure 2) was developed by Bodymonitor, a spin-off from Gesis Leibniz-Institute for the Social Sciences, as a tool to measure peripheral body signals like electrodermal activity (EDA) and skin temperature as indicators of primary emotional responses like stress and interest.

The sensor wristband captures and saves local skin conductivity and skin temperature at a rate of 10 Hz with 10-bit resolution. Preparation of the data consists of two steps. First, artifacts in skin conductivity and skin temperature caused by changing contact quality of skin and transducers are detected (this is possible because skin contact quality

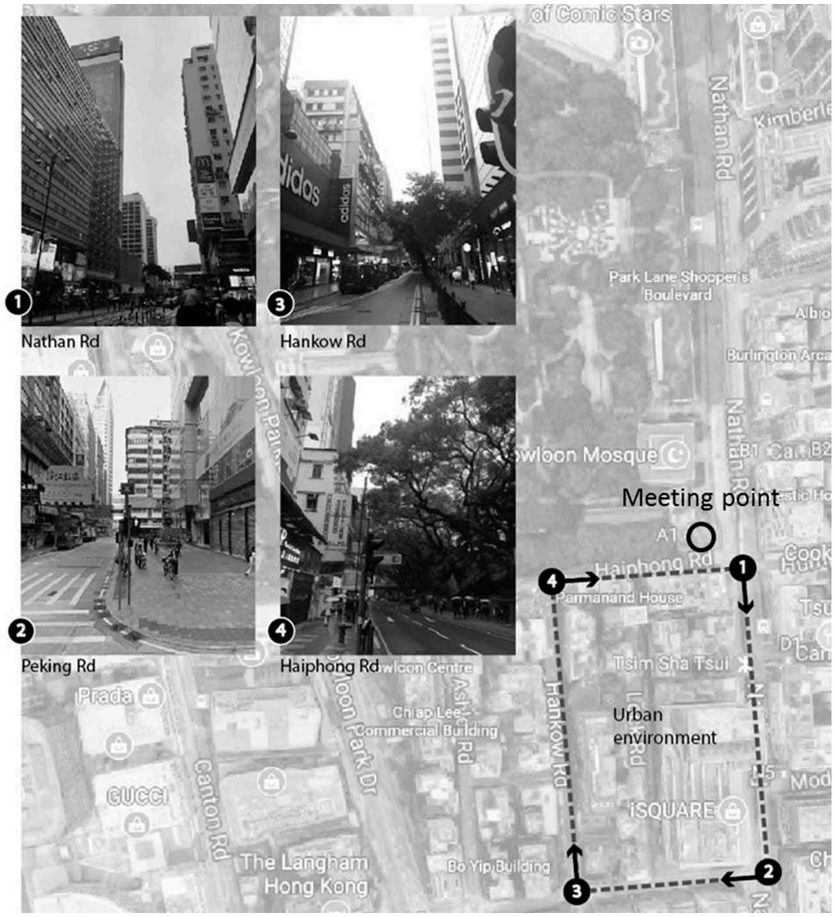

Figure 1. Map of walking route with 4 street paths.

and ambient temperature are measured). Second, the individual variations in EDA level are standardized as proposed by Lykken and Venables (1971) in order to establish a baseline for each participant.

The validity of capturing electrodermal arousal via the smart-band was confirmed by experimental research and by several field studies (Bergner et al., 2013; Bergner, Zeile, Papastefanou, Rech, & Streich, 2011; Hogertz, 2010; Li et al., 2016; Steinitz, 2014). The sensor wristband comes with a classification algorithm, which was developed by Papastefanou (2018) from the background of the biopsychological framework of emotion described above. In this framework (Ekman, 1992; Levenson, 2003), physiological responses are a central dimension in the manifestation of neuro-affective appraisal of stimuli. Levenson, Carstensen, Friesen, and Ekman (1991) and Kreibig's (Kreibig, 2010, 2014) reviews show that specific emotional states are correlated with specific physiological arousal reflected in peripheral parameters like skin conductivity, skin temperature, and heart rate variability. This means that a kind of elementary valence (aversive vs. appetitive) of physiological emotion responding can be identified (Table 1). Basic emotions like anger,

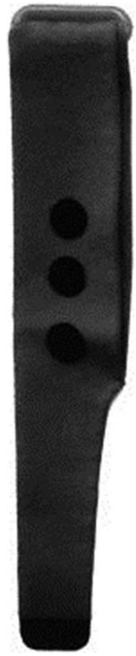

Figure 2. Sensor wristband.

fear, happiness, and sadness are also associated with distinct patterns of physiological changes (Rainville, Bechara, Naqvi, & Damasio, 2006).

From these studies, EDA seems to be the most simple and effective indicator of emotional arousal. EDA reflects sweat gland activity, which is directly enervated by neural signals of the sympathetic nervous systems, while sympathetic nervous excitation is closely connected to brain structures of neuro-affective negative (avoidance) or positive (approach) appraisal (Boucsein, 1995; Boucsein & Backs, 2009). While it is experimentally verified that EDA as a single parameter allows identifying stress reactions (Papastefanou, 2013; Setz et al., 2010), EDA changes cleaned for artifacts and noise can also be used validly for identifying emotional responses to aversive and appetitive stimuli (Hijazi et al., 2016). For further corroboration, we calculated mean response strength for aversive and appetitive responses to different audiovisual stimulations (based on images and sounds of the IAPS and IADS). Results in Figure 3 confirm that negative and positive appraisal can be differentiated by EDA.

Table 1. Typology of aversive and appetitive EDA emotions.

EDA based emotion response type	“feelings” connotations
Appetitive arousal ("orientation, surprise, expecting reward")	Joy, curiosity, surprise, newness
Aversive arousal ("Flight-Fight-Response, expecting loss")	Fear, anger, tension, stress, discomfort
Balance	Vigilance, well-being, hedonic pleasure
Retraction	Shut-off, dis-interested, mental withdrawal, tired, deeply relaxed

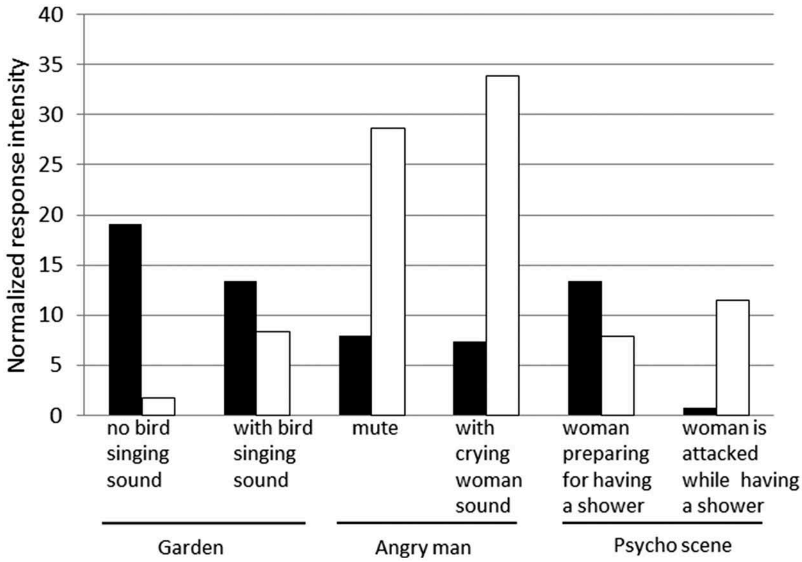

Figure 3. Intensity of aversive and appetitive EDA-response by ground truth emotion induction stimuli. Notes: Black denotes appetitive responses, white denotes aversive responses, n = 30, own calculations.

As this classification is based on signal data with a 10 Hz resolution, we get a database with moments of a 10^{th} of a second as basic observation units. Thereby, we have a hierarchical level data set with subjects and their moments of time over the whole observation period. For each moment of time, there is information available about the emotional class of a given arousal response. This data on emotion reaction occurrence can be used as binary (yes vs. no occurrence) as well as metric information (momentary strength of the response).

Indicating crossing personal space by passive infrared sensor

In addition to psychophysiological sensors, the sensor-band was extended by an infra-red motion sensor. Its technical design and body positioning allowed for detecting people crossing the personal space at varying distances. We used the slight motion type of passive infrared sensor by Panasonic (NaPiOn) designed to cover a wide area, to detect human presence in an ambient space of up to 2 m distance from sensor position (see Figures 4 and 5). The sensor, rather than emitting light such as from LEDs, detects the amount of change in infra-red rays that occurs when a person (object), whose temperature is different from the surroundings, moves. As this sensor detects temperature differences, it is well suited to detecting the motion of people by their body temperature (see Figure 6). The infrared sensor was positioned about the level of the subjects' sternum and it responds with a signal when a person moves through the conical space sensitivity.

When people move through the sensitive space, the sensor outputs a signal, which is stored locally in the wristband (along with signals of the other sensors). This signal was transformed into yes/no information for each moment of data collection. The data

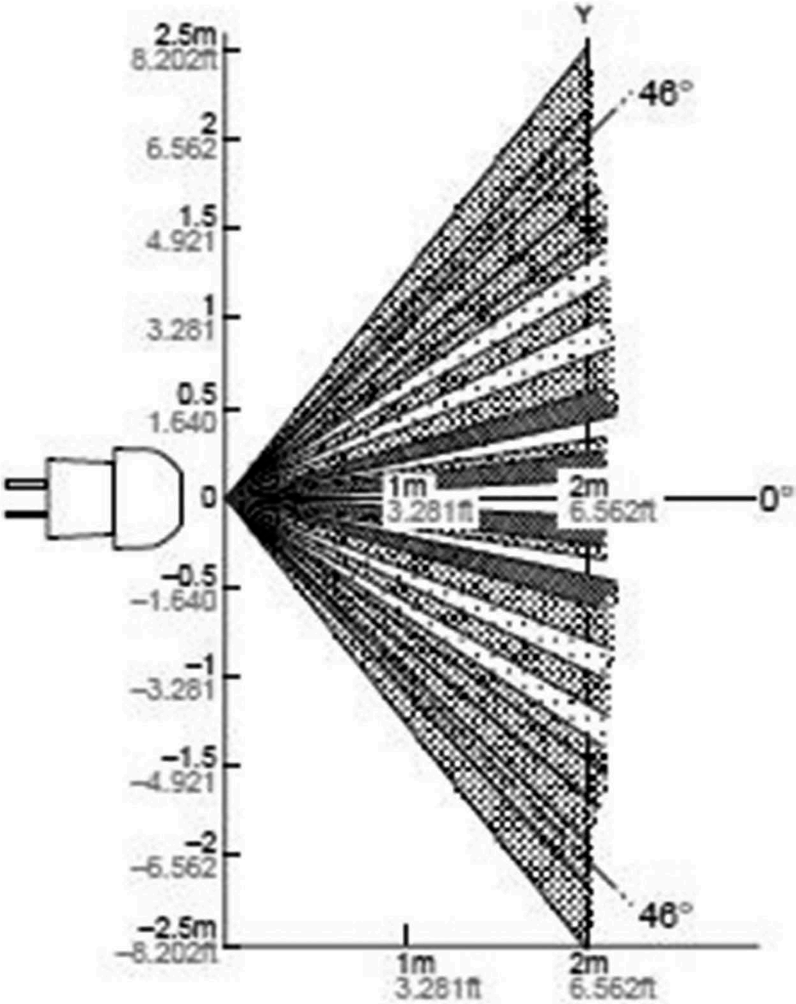

Figure 4. Detection sensitivity space of slight movement detection of the passive infrared sensor.

collection moments were given by 10 Hz recording. These moments are the units of observations in a hierarchically structured data set with subjects as top level.

Data set and statistical analysis

The data set is built up by psychophysiological as well as passive infrared motion sensor signals at a rate of 10 Hz. So, after emotion classification of electrodermal signals and motion detection signals, for each 10th of a second over the whole observation period of walking the urban street route, we reduced the data to binary information about the occurrence of an emotional response and a motion in the 2 m personal space. Due to the hierarchically structured data set, we run multilevel statistical analysis by modeling the covariation of personal space movement as a mixed regression model with random intercept. As EDA phasic responses typically show a bell curve shape over time, we choose

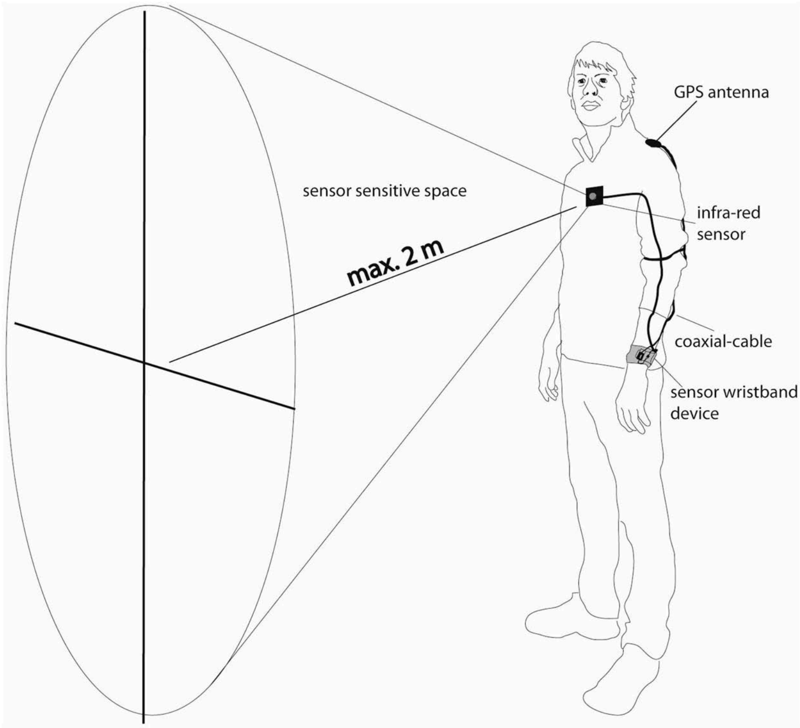

Figure 5. Sensors and wristband body positioning and indication of sensor-based person space.

the amplitude maximum as a binary indicator of emotion response occurrence. For dealing with binary dependent variables, we use the logit model. In this model, binary information about moving through the 2 m personal space is incorporated as an independent variable. Since we do not have information about the distance of persons entering the personal space, we used additional lagged information about personal space crossing as a proxy. In an exploratory manner, we included five lagged entry variables, namely at the moment simultaneously with the emotional response, and 1 to 5 s before. Finally, to control for an accumulation of emotional responsivity over the street paths we included path duration information for each.

Results

Crossing personal space as crowd-density indicator

First, we regard the time subjects needed to walk down the predefined streets. We find clear differences between the street paths, with street path 3 which subjects needed most time to walk down and street path 4 with least walking time (Table 2). These differences are due to the length of the street paths and their crowdedness.

The signal data of the motion sensor shows different frequencies of personal space crossings while walking (Table 3). Taking the ratio of the mean number of personal space crossing to the street length (in meters), we get an indicator of crowd density as being experienced by pedestrians. Street path 2 and street path 4 could be labeled as most crowded.

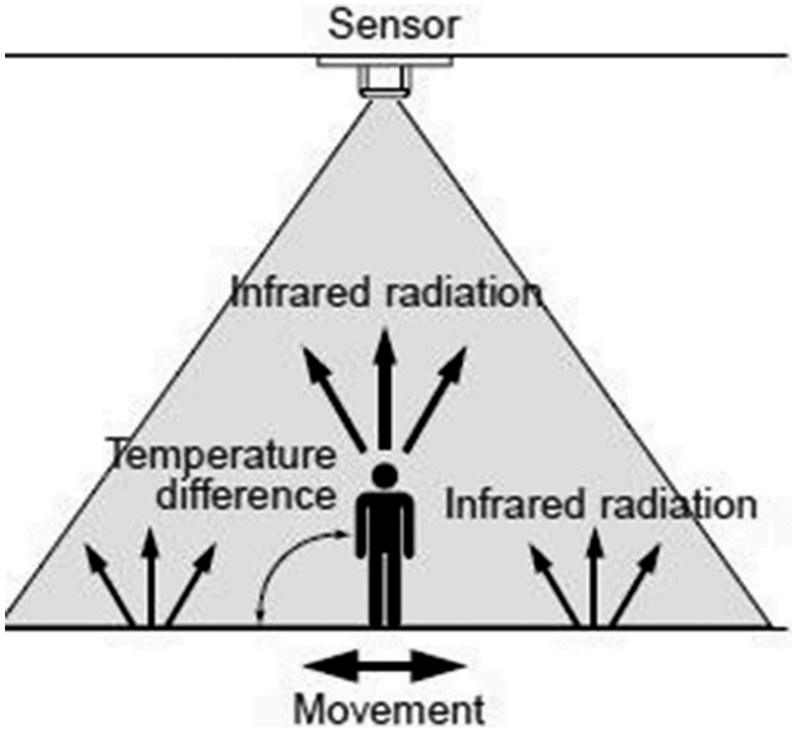

Figure 6. Movement detection mechanism by passive infrared sensor.

Effects of personal space crossings on emotional responding

To analyze the relationship between personal space crossing and emotional responding, we estimated the odds ratios of emotional response occurrence at each moment (namely a 10th of a second), predicted by preceding occurrence of personal space crossing by other pedestrians. Hypothesis 1 assumes that personal space invasions elicit aversive emotional responses. In support of our hypothesis, we find for model 1, which is based on data of the whole walking route, that subjects who experience personal space crossings subsequently –

Table 2. Mean walking duration in different street paths.

Street path	Mean duration in minutes	Physical length (meter)
Street path 1	4.2	178
Street path 2	4.8	96
Street path 3	5.4	178
Street path 4	3.5	96

Table 3. Mean number of personal space crossings while walking in different street paths.

Street path	Mean number of personal space crossings	Mean personal space crossings per meter
Street path 1	36.4	0.20
Street path 2	24.1	0.25
Street path 3	38.8	0.22
Street path 4	25.2	0.26

namely in the next 2 s – will have an increased probability to elicit an aversive emotional response (Table 4).

However, this holds only for street paths 1 and 4. For street paths 2 and 3, we do not find any significant effect of personal space crossing on subsequent emotional responding. Interestingly, in street path 1, the aversive emotional response occurs simultaneously with personal space crossing, whereas in street path 4, an aversive response is elicited 1–2 seconds after personal space crossing.

Crossing one's personal space causes people to become aware of others approaching them, i.e., personal space crossings attract attention. Findings in Table 4 show that subjects automatically respond with aversive arousal. However, as stated in hypothesis 2, approaching people who get close by crossing the personal space might also elicit curiosity or interest, generally appetitive. Next, we therefore examine if personal space crossing also triggers appetitive responses. In Table 5, results are reported for the whole route (model 1) and the four street paths separately (models 2–5).

For the whole route moments, we find no significant relationship between crossing personal space and appetitive responding, maybe due to heterogeneity of the street paths. Namely, we find a significant effect of personal space crossing on the appetitive response when walking in street paths 1 or 2, but not in street paths 3 or 4. For street path 2, we even find a prolonged effect of personal space crossing up to second 3 after crossing. This lag effect means that, as people come closer, they even get more interesting. For street path 1, we find a significant increased appetitive response probability simultaneous with personal space crossing. Therefore, hypothesis 2 is partially supported.

Table 4. Effects of personal space crossing on occurrence of aversive emotional response while walking in urban street paths (odds ratios, mixed effects logit models).

	Model 1	Model 2	Model 3	Model 4	Model 5
Variables	Total route	Street path 1	Street path 2	Street path 3	Street path 4
Crossing Personal	1.183***	1.351**	1.051	0.943	1.273*
Space (PS) (no lag)	(0.077)	(0.169)	(0.153)	(0.115)	(0.171)
Crossing PS	1.139**	0.94	1.212	1.061	1.188
1-second lag	(0.0751)	(0.133)	(0.168)	(0.125)	(0.163)
Crossing PS	1.146**	1.221	1.17	0.856	1.270*
2-second lag	(0.0755)	(0.158)	(0.165)	(0.108)	(0.171)
Crossing PS	1.012	0.979	0.942	0.901	1.084
3-second lag	(0.0696)	(0.136)	(0.143)	(0.112)	(0.153)
Crossing PS	1.04	1.182	0.951	0.81	1.128
4-second lag	(0.0708)	(0.155)	(0.145)	(0.104)	(0.157)
Crossing PS	1.093	1.057	0.913	1.027	1.178
5-second lag	(0.0732)	(0.143)	(0.141)	(0.121)	(0.162
Subjects	1.200***	1.629***	1.275***	1.296***	1.220***
variation	(0.057)	(0.211	(0.082)	(0.0883)	(0.0648)
Constant	0.0752***	0.0754***	0.0604***	0.0669***	0.0669***
	(0.00593)	(0.00983)	(0.00568)	(0.00643)	(0.00577)
Observations	287,641	54,941	80,790	93,140	58,740
Number of subjects	30	30	30	30	30

Notes: SE of logit coefficients in parentheses, models controlled for momentary duration of path.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 5. Effects of crossing personal space on occurrence of appetitive emotional response while walking in urban street paths (odds ratios, mixed effects logit models).

	Model 1	Model 2	Model 3	Model 4	Model 5
Variables	Total route	Street path 1	Street path 2	Street path 3	Street path 4
Crossing Personal	1.061	1.287*	1.428***	0.818	0.848
Space (PS) (no lag)	(0.0784)	(0.18)	(0.196)	(0.12)	(0.155)
Crossing PS	0.979	0.972	0.947	1.074	0.934
1-second lag	(0.0746)	(0.151)	(0.151)	(0.141)	(0.164)
Crossing PS	1.104	0.953	1.314*	1.182	0.995
2-second lag	(0.0804)	(0.15)	(0.186)	(0.149)	(0.17)
Crossing PS	1.05	0.86	1.371**	1.087	0.93
3-second lag	(0.078)	(0.141)	(0.191)	(0.142)	(0.163)
Crossing PS	1.033	1.134	1.111	0.995	0.952
4-second lag	(0.0771)	(0.167)	(0.168)	(0.134)	(0.165)
Crossing PS	0.860*	0.699**	0.85	0.897	1.075
5-second lag	(0.0691)	(0.125)	(0.143)	(0.126)	(0.178)
Subjects	1.086***	1.129***	1.423***	1.104***	1.158***
variation	(0.0237)	(0.0392)	(0.14)	(0.0301)	(0.0477)
Constant	0.0838***	0.0857***	0.0694***	0.0751***	0.102***
	(0.00451)	(0.00585)	(0.00775)	(0.00468)	(0.00763)
Observations	287,641	54,941	80,790	93,140	58,740
Number of subjects	30	30	30	30	30

Note. SE of logit coefficients in parentheses, models controlled for momentary duration of path.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Discussion and conclusions

From the background that personal space seems to be an important concept for understanding emotional dynamics in high-density streets, we for the first time used a sensor device to indicate dynamically personal space of subjects walking in an urban street. Personal space is thereby operationally defined as the sensitivity area of a passive infrared sensor for slight motions with a maximum distance from the subject of 2 m. Crossing this sensitive area equals an intrusion of the subjective personal space. Our findings show that this sensor approach is feasible and provides meaningful results: it can be used to calculate an indicator of experienced crowd density. The difference of experienced crowd density ratio between the different street paths of the test route is a preliminary result which supports its validity.

We examined the relationship between personal space and emotional responding and find significant effects of personal space crossing on aversive and appetitive emotional responses, based on EDA arousal classification. Walking in crowded streets as they are typical for business districts, leads to a series of involuntary personal space crossings, which then evokes aversive emotions, as assumed by proximity theory. Notably, we found this effect although people are expecting personal space invasion in highly crowded streets which should reduce the effect of personal space invasion (Wollman et al., 1994). Personal space crossing also leads to appetitive emotional responses which points to some neglected aspect of the functioning of personal space – its meaning as an area which defines the subjective relevance of encountering other people by chance. When people come close into one’s ambient personal space, arousal processes start and lead to aversive responses but also to appetitive responses. The urban context plays a significant role to when an occurrence of personal space crossing is emotionally evaluated as negative or positive (in the meaning of interest).

One limitation of this study is that by the present analysis, we cannot uncover the specific aspect of the different street paths of the test route, to make personal space crossing eliciting aversive or appetitive responses. But as the data of the Hong Kong study also measured geo-position on a second-by-second level, a further step in analyzing urban antecedents of personal space emotion effect could be done. Dynamic geo-position data of longitude and latitude can be used to operationally define small urban spatial segments of walking in the street. Then, the relationship between personal space crossings and emotional response could be examined for specific street segments and their urban structural characteristics.

Second, our sample was very closely defined because this study was conducted in Hong Kong with a Chinese population. Since there are cultural differences in the perception of crowding and personal space invasions (Beaulieu, 2004; Sussman & Rosenfeld, 1982), replicating our study in high-density cities with different cultural contexts, like New York, Mumbai, or Mexico City would be insightful.

Another limitation concerns the use of data source as we focused solely on objective psychophysiological data and did not collect additional self-report data. This can be considered a limitation because emotional valence and crowding involve subjective labeling. Nevertheless, gathering self-report measures was not necessary here for three reasons. First, it is impossible to receive self-report data with that high time resolution (remember that our sensor band measured parameters 10 times a second), so the physiological data is much more accurate at a time level than self-report could have been. Second, self-report measures are susceptible to impression management and lack of introspection. Psychophysiological measures cannot be manipulated that easily, and no introspection is needed. Third, since the classification system of emotions used here has been validated in various studies (e.g., Bergner et al., 2013; Li et al., 2016; Steinitz, 2014), it is not necessary to collect additional self-report data.

Since this was the first study to examine the relationship between crowding and emotional response physiologically, we did not analyze the effect of different designs of the environment on the emotional response. We focused on the question if crowded streets are able to elicit different types of emotional responses. Future research should take into account how the environment is shaped, for example, via an isovist or by comparing different landscape styles, e.g., urban and natural. Since we have also collected data on walking routes in a park, in a further study, we could compare if natural environments elicit different emotional response patterns than urban environments.

Future research could also examine if it matters, in which direction people are walking when they enter the personal space because one could argue intuitively that someone walking past is less severe than someone walking towards oneself. The sensor device used in this study is not able to determine the entering direction, but further devices and other body positions of the device should be considered, for example, attaching an additional infrared device on the back of the subject.

Showing that personal space can be validly measured by body sensors opens up further analyses about how moving in crowded streets elicits emotional responses, whose accumulation over the path walked might add to what people finally feel as stress load in high-density urban areas. As data on psychological outcomes after having walked in urban streets are available by the Hong Kong study, another analysis can focus on how reactions accumulate and determine subjective feelings of reduced attention performance and heightened stress load over the sequence of involuntary and non-controllable invasions.

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