Aus dem Zentralinstitut für Seelische Gesundheit
der Medizinischen Fakultät Mannheim
(Direktor: Prof. Dr. med. Andreas Meyer-Lindenberg)

Neural correlates of real-life affective resilience measures in healthy community-based individuals

Inauguraldissertation
zur Erlangung des Doctor scientiarum humanarum (Dr. sc. hum.)
der
Medizinischen Fakultät Mannheim
der Ruprecht-Karls-Universität
zu
Heidelberg

vorgelegt von
Ren Ma
aus
Anhui, China
2021

Dekan: Prof. Dr. med. Sergij Goerdt

Referentin: Prof. Dr. med. Dr. phil. Heike Tost

TABLE OF CONTENTS

ABBREVIATIONS

AAL	Automated Anatomical Labeling
ACC	Anterior cingulate cortex
BOLD	Blood-oxygen-level dependent
CAT	Computational Anatomy Toolbox
DARTEL	Diffeomorphic Anatomical Registration through Exponentiated Lie algebra
FD	Framewise displacement
fMRI	Functional magnetic resonance imaging
FWE	Family-wise error
HPA	Hypothalamic–pituitary–adrenal
MID	Monetary incentive delay
Mini-DIPS	Diagnostisches Kurz-Interview bei psychischen Störungen
MNI	Montreal Neurological Institute
MPRAGE	Magnetization-Prepared Rapid Acquisition Gradient-Echo
MRI	Magnetic resonance imaging
PCA	Principal Component Analysis
ROI	Region of interest
SAB	Social affective benefit
SCID-IV	Structured Clinical Interview for DSM-IV
SPM	Statistical Parametric Mapping
TIV	Total intracranial volume
VBM	Voxel-Based Morphometry
VS	Ventral striatum
VTA	Ventral tegmental area

1 INTRODUCTION

Affective well-being is a general mood state that is important for mental and physical health (Insel et al., 2010; WHO, 2005). From an evolutionary perspective, affective well-being is highly conserved across species (Nettle & Bateson, 2012), suggesting an adaptive role of affective well-being in survival and reproduction. Disturbance of affective well-being is a main underlying feature of many psychiatric disorders, which contribute significantly to the overall global burden of disease and are a leading cause of disability (Rehm & Shield, 2019). Notably, low affective well-being also facilitates the development of physical illness. Over decades, studies have associated premorbid depressed mood with an elevated risk for cancer morbidity and mortality (Kaplan & Reynolds, 1988; Knekt et al., 1996; Penninx et al., 1998; Zonderman, Costa, & McCrae, 1989), and depressive symptoms with severe cellular immunity damage (Herbert & Cohen, 1993; Zorrilla et al., 2001). On the other hand, there is tremendous evidence highlighting the beneficial effect of positive affect on mental and physical health such as reduced stress (Saslow, Cohn, & Moskowitz, 2014), higher confidence and optimism (Lyubomirsky, King, & Diener, 2005), increased longevity, lower morbidity, and decreased pain (Cohen & Pressman, 2006; Pressman & Cohen, 2005). Therefore, investigating how to maintain stable levels of affective well-being in real life is an important research topic in psychiatry and clinical psychology.

Resilience refers to a process of positive adaptation to stress or adversity (Rutter, 2006, **Figure 1.1**). According to the theoretical framework proposed by Kalisch et al. (2015), resilience is influenced by internal resources such as optimism (Segovia, Moore, Linnville, Hoyt, & Hain, 2012), self-efficacy (Schwarzer & Warner, 2013), active coping strategies (Smith & Carlson, 1997), and external resources including social support (Hefner & Eisenberg, 2009), positive events (Doorley et al., 2020; Grosse Rueschkamp, Kuppens, Riediger, Blanke, & Brose, 2020), physical activity (Kanning & Schlicht, 2010; Liao, Shonkoff, & Dunton, 2015; Reichert et al., 2020; Wichers et al., 2012), and green space exposure (Bratman, Hamilton, Hahn, Daily, & Gross, 2015; Tost et al., 2019; White, Alcock, Wheeler, & Depledge, 2013). Compared to internal resources, external resilience resources can be monitored relatively well using innovative digital technologies and may even be targets for experimental modification. Thus in the present dissertation I invested the assumed impacts of real-life external resilience resources on affective well-being, for which I coined a term “real-life affective resilience

measures". While there is a lot of research investigating real-life affective resilience measures, specifically at the between-subject level (Cohn, Fredrickson, Brown, Mikels, & Conway, 2009; Schwarzer & Warner, 2013; Smith & Carlson, 1997), research has only begun to assess within-subject fluctuations of affective resilience measures in everyday life in naturalistic environments (Ebner-Priemer & Trull, 2009; Trull & Ebner-Priemer, 2013). Although there are already a few studies investigating a link between the real-life affective resilience measures and biological markers of psychiatric disorders (Bratman et al., 2015; Park et al., 2007; Reichert et al., 2020; Tost et al., 2019), this multimodal research approach is still in its infancy. Thus, studies with well-powered samples are needed to better understand how real-life affective resilience measures are associated with brain structure and brain activity.

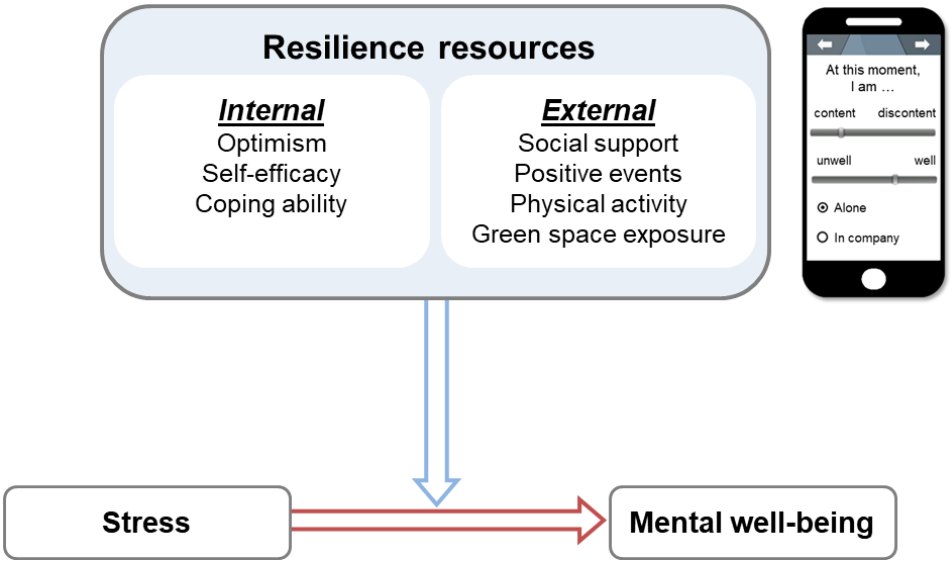

Figure 1.1. A conceptual theoretical framework of resilience based on the social buffering hypothesis proposed by Cohen & Wills (1985). Cohen & Wills (1985) proposed that social support was thought to buffer against the adverse effects of stress. More recent work highlights additional resilience resources including optimism, self-efficacy, coping ability, positive events, physical activity, and green space exposure. Kalisch et al. (2015) suggested that these resilience resources can be categorized as internal and external. Importantly, data of resilience resources and mental well-being can be assessed with smartphone-based ambulatory assessment in everyday life in naturalistic environments. The figure was conceptualized by the doctoral candidate based on the social buffering hypothesis (Cohen & Wills, 1985) and the categorization of resilience resources suggested by Kalisch et al. (2015). The figure of smartphone was adapted from Gan et al. (2021).

1.1 Real-life external resilience resources for mental health

A growing number of studies have addressed the association between external resilience resources and affective well-being (Bratman et al., 2015; Kanning & Schlicht, 2010; Liao et al., 2015; Reichert et al., 2020; Tost et al., 2019; White et al., 2019; White et al., 2013; Wichers et al., 2012). Among these, physical activity and green space exposure have been consistently reported to increase affective well-being (Koch et al., 2018; Reichert et al., 2020; Tost et al., 2019; White et al., 2019), and there is first evidence for underlying neurobiological substrates of these real-life affective resilience measures (Reichert et al., 2020; Tost et al., 2019). In contrast, researchers have paid much less attention to social contact and positive events in the context of real-life resilience measures, and their respective neural bases remain unknown. Thus, in this dissertation, I examined the impacts of social contact and positive events on daily-life affective well-being, the associations of these real-life resilience measures with brain structure and brain function, and its relevance for psychiatric risk and resilience.

1.1.1 Social contact

Humans are inherently social creatures. Individuals with a supportive social network can get social support from friends, family, and significant others in stressful life situations (Hefner & Eisenberg, 2009). The social buffering hypothesis proposed that supportive social relationships with other people can buffer the adverse effect of stressful experiences or negative emotions, and thus preserve mental and physical health (Cohen & Wills, 1985; Mitchell, Billings, & Moos, 1982). High-quality social relationships have been shown to contribute to mental health (Hefner & Eisenberg, 2009) and were linked to a reduced risk of mortality (Hefner & Eisenberg, 2009; Holt-Lunstad, Smith, & Layton, 2010). In contrast, loneliness or social isolation have significant implications for all-cause mortality (Rico-Uribe et al., 2018), psychological distress (depression, anxiety), and suicidal ideation (Beutel et al., 2017; Cacioppo, Hughes, Waite, Hawkley, & Thisted, 2006). Real-life ambulatory assessment studies reported that individuals showed increased positive affect (Brown, Silvia, Myin-Germeys, & Kwapil, 2007; Oorschot et al., 2013) and decreased negative affect (Brown et al., 2007; Husky, Grondin, & Swendsen, 2004; Kwapil et al., 2009; Oorschot et al., 2013) when in the company of others as compared to being alone. While individuals with social deficits such as social anxiety and social anhedonia are alone more often (Oorschot et al., 2013), an emotional benefit from social contact was consistently

shown across healthy and clinical populations with such social deficits (Brown et al., 2007; Husky et al., 2004; Kwapil et al., 2009; Oorschot et al., 2013). Thus, social contact represents an important external resilience resource for affective well-being in healthy individuals as well as in individuals with severe social deficits. In study 1, I referred to the effect of increased affective well-being during social contact as “social affective benefit”. While social affective benefit is a fundamental real-life affective resilience measure, its neural basis and implications for psychiatric risk and resilience are under-researched.

1.1.2 Positive events

Another powerful external resilience resource for affective well-being is the experience of positive events. There is accumulating evidence from ambulatory assessment studies that momentary affect increases in response to experienced daily-life positive events in both psychiatric patients and healthy populations (Bylsma, Taylor-Clift, & Rottenberg, 2011; Grosse Rueschkamp et al., 2020; Khazanov, Ruscio, & Swendsen, 2019; Peeters, Nicolson, Berkhof, Delespaul, & deVries, 2003). This concept of increased positive affect in response to positive events has been termed “affective reactivity to positive events” (Grosse Rueschkamp et al., 2020), a term that I will use throughout this dissertation. Importantly, Peeters and colleagues (2003) revealed a "mood brightening" effect by showing that depressed individuals reported larger increases in positive affect in response to daily-life positive events than healthy controls. A comparable mood brightening effect was reported in an independent depressed sample, and the mood brightening effect of positive events was related to the severity of depression (Khazanov et al., 2019). Similar evidence also comes from studies in the general population, in which individuals with lower affective well-being profited more from the joy of daily-life positive events (Grosse Rueschkamp et al., 2020). Notably, increased affective reactivity to positive events has been shown to preserve mental health from exposure to childhood adversity or recent stressful life events (Geschwind et al., 2010). Taken together, these findings suggest that daily-life positive events represent an important external resilience resource for affective well-being that may protect against depression or low emotional well-being in daily life.

1.2 Assessment of real-life affective resilience measures

Traditional assessment methods of affective states and resilience resources depend on retrospective self-reports (Ebner-Priemer & Trull, 2009), where individuals report these measures purely based on the recall from their memories, often in a laboratory-based context. The time interval between the original moment and the recall may range from 24 hours to several years (Ebner-Priemer & Trull, 2009). One significant problem of these traditional methods is recall bias, such that recall is often formed by biased storage and recollection of memories (Fahrenberg, Myrtek, Pawlik, & Perrez, 2007; Fredrickson, 2000; Stone & Broderick, 2007). Moreover, cross-sectional and retrospective methods cannot precisely assess dynamic affective processes and identify under which circumstances affective well-being may be undermined or be promoted (Ebner-Priemer, Eid, Kleindienst, Stabenow, & Trull, 2009). Thus, novel digital research tools can help to overcome these limitations.

1.2.1 The need for ambulatory assessment

The method of choice to investigate affective reactivity to daily-life resilience resources and circumvent retrospective biases is ambulatory assessment. Scientists use different names for this assessment methodology including ecological momentary assessment (Shiffman, Stone, & Hufford, 2008), experience sampling method (Csikszentmihalyi & Larson, 1987), ambulatory assessment (Fahrenberg et al., 2007), or real-time data capture (Stone & Broderick, 2007). Even though the terms differ, these approaches commonly use digital devices (e.g., smartphones) to acquire ecologically valid data such as mood, symptoms, behaviors, or physiological processes during daily-life activities (Trull & Ebner-Priemer, 2013). Throughout this dissertation, I use the term “ambulatory assessment”.

Ambulatory assessment has many distinct features that outperform traditional retrospective and laboratory-based assessment approaches. Ambulatory assessment collects data in naturalistic situations that cannot be recreated in the laboratory, thus improving the ecological validity of findings. Another advantage is that ambulatory assessment can capture individuals' momentary affective states or behaviors in real-time, thereby minimizing retrospective biases that often undermine the reliability of data gathered using traditional single-occasion retrospective self-reports. It was shown that the accuracy of momentary reports is significantly increased compared to

retrospective questionnaire reports (Schwarz, 2012; Solhan, Trull, Jahng, & Wood, 2009). Ambulatory assessment also allows for examining the within-subject dynamic change of individual psychological and behavioral processes by collecting repeated assessments over specific time windows, compared to cross-sectional reports. Beyond these advantages, ambulatory assessment studies can sample participants' mood, experiences, and behavior, as well as simultaneously monitor information about the environment (e.g., geolocation [urban vs. rural], population density) and situational context (e.g., at home, at work) that may influence the variable of interest.

Given the repeated assessments over time, ambulatory assessment data are organized in a longitudinal and hierarchical format (e.g., assessments are nested within persons). Analysis of ambulatory assessment data thus requires advanced statistical methods such as multilevel modelling that can handle a hierarchical data structure and are robust against missing data (Wilhelm, 2001). Multilevel models are also known as hierarchical linear models, linear mixed-effect models, mixed models, or random-effects models. Multilevel modelling enables the estimation of within- (random) and between-subject (fixed) effects simultaneously in one statistical model. Moreover, when modeling time-relevant changes in affective processes, multilevel models can treat time flexibly, thus allow the modeling of non-linear and discontinuous change across time and accommodate uneven spacing of time points and unequal numbers of observations across individuals.

1.2.2 Affective well-being in real life

There are different established scales to measure affective well-being in daily life using ambulatory assessment. Here, I will focus on the most widely used and established scales for ambulatory assessment including the Positive and Negative Affect Scales (PANAS, Watson, Clark, & Tellegen, 1988) and the Multidimensional Mood State Questionnaire (Mehrdimensionale Befindlichkeitsfragebogen, MDBF, Steyer, Schwenkmezger, Notz, & Eid, 1997). These two scales have been used in ambulatory assessment studies to assess affective reactivity to positive events (Bylsma et al., 2011; Geschwind et al., 2010; Grosse Rueschkamp et al., 2020; Peeters et al., 2003; Wichers et al., 2010), as well as the effects of social contact on affective well-being (Brown et al., 2007; Husky et al., 2004; Kwapil et al., 2009; Oorschot et al., 2013).

Watson and Tellegen (1985) proposed that mood can be defined by two dominant dimensions: positive affect (e.g., active, excited, enthusiastic) and negative affect (e.g.,

distressed, guilty, upset). The PANAS was developed with two 10-item scales to measure each dimension (Watson et al., 1988). Since its development in the 1980s, the PANAS has been widely used to measure affect in psychiatric patients and healthy individuals (Heubeck & Boulter, 2021; Hughes & Kendall, 2009; Kitsantas, Gilligan, & Kamata, 2003; Mackinnon et al., 1999). In ambulatory assessment studies with healthy and psychiatric populations, positive affect is one of the most widely used measures of affective well-being (Myin-Germeys et al., 2003; Myin-Germeys & van Os, 2007; Myin-Germeys, van Os, Schwartz, Stone, & Delespaul, 2001; Wichers et al., 2009; Wichers et al., 2007; Wichers et al., 2010).

However, the basic assumption that two orthogonal dimensions can sufficiently capture mood was criticized by some researchers (Matthews, Jones, & Chamberlain, 1990; Russell & Carroll, 1999; Schimmack & Grob, 2000). Based on the Multidimensional Mood State Questionnaire (Steyer et al., 1997), a scale with three basic dimensions was developed for ambulatory assessment: valence (V; ranging from unpleasant to pleasant), calmness (C; ranging from restless/under tension to calm/relaxed), and energetic arousal (E; ranging from tired/without energy to awake/full of energy) (Matthews et al., 1990; Schimmack & Grob, 2000; Wilhelm & Schoebi, 2007). Since its development, the MDBF has also been widely used in ambulatory assessment studies to capture dynamic changes of mood in healthy and psychiatric populations (Koch et al., 2018; Reichert et al., 2020; Tost et al., 2019) and has been shown to have excellent reliability criteria (Wilhelm & Schoebi, 2007).

1.2.3 Affective resilience measures in real life

To assess the affective reactivity in response to resilience resources such as social contact or positive events, researchers typically ask participants to repeatedly rate their affective states and indicate if they are in social contact at the moment or if they have experienced any positive event since the last assessment (Brown et al., 2007; Bylsma et al., 2011; Grosse Rueschkamp et al., 2020; Oorschot et al., 2013; Peeters et al., 2003). As outlined in section 1.2.1, researchers can estimate fixed and random effects of resilience resources (e.g., social contact, positive events) on momentary affective well-being (e.g., positive affect, valence) using multilevel modelling. While fixed effects indicate the effects of the resilience resources on affective well-being across a group of individuals, adding random effects to the multilevel model allows the association between resilience resources and affective well-being to vary across different

individuals. Random effects thus offer the possibility to estimate individual levels of real-life affective resilience measures that can be used in follow-up analyses. For example, previous studies computed the random effects of positive event intensity on momentary affective well-being as individual levels of affective reactivity to positive events in both patients and healthy individuals (Bylsma et al., 2011; Grosse Rueschkamp et al., 2020; Peeters et al., 2003). Moreover, previous neuro-epidemiological studies combining ambulatory assessment with neuroimaging included individual slopes representing the random effect of green space exposure (Tost et al., 2019) or non-exercise activity (Reichert et al., 2020) on daily-life affective valence as regressors of interest in multiple regression models to assess associations with brain structure and function (see section 1.3 for a detailed description).

1.3 Neural correlates of real-life affective resilience measures

Neuro-epidemiological approaches combining ambulatory assessment, neuroimaging, and the assessment of social and psychological risk and resilience for psychiatric disorders offer a way forward to better understand the neural bases of fundamental real-life affective resilience measures that I introduced above. Previous work employing neuro-epidemiological approaches showed that the affective benefits of green space exposure were associated with prefrontal activity during negative-emotion processing (Tost et al., 2019). Also, Reichert et al. (2020) demonstrated that the volumetric change in the subgenual anterior cingulate cortex (ACC) mediated real-life effects of non-exercise physical activity on affective well-being. These studies highlight that real-life affective changes in response to resilience resources map to stress-regulatory neural circuits previously associated with psychiatric risk and resilience (Akdeniz et al., 2014b; Holz, Tost, & Meyer-Lindenberg, 2020; Lederbogen et al., 2011). While there is sound evidence from laboratory-based magnetic resonance imaging (MRI) studies about the neural circuits involved in social contact and processing rewarding stimuli, the neural bases of real-life affective responses to social contact and positive events are under-researched.

1.3.1 Brief introduction into (functional) magnetic resonance imaging

The progress in non-invasive neuroimaging technology in the last several decades enables imaging *in vivo* brain structure and the measurement of brain activity while an individual is resting or engaging in processing emotional stimuli or navigating social

situations. MRI is one of the most widely used non-invasive imaging techniques in human psychiatry research and cognitive neuroscience. MRI uses strong static magnetic fields from the MRI scanner, magnetic gradients from gradient coils, and oscillating electromagnetic fields from radiofrequency coils to generate *in vivo* brain images. Specifically, when a human body is placed into an MRI scanner, the magnetic moments of hydrogen nuclei within the human body are aligned with the static magnetic fields, thus reaching an equilibrium state. Then radiofrequency coils generate electromagnetic fields at the resonant frequency of the hydrogen nuclei to perturb this equilibrium state, a process known as excitation. During this excitation time, the hydrogen nuclei absorb the energy of the radiofrequency pulse. When the radiofrequency pulse ends (i.e., electromagnetic fields are turned off), the hydrogen nuclei release the absorbed energy and return to the equilibrium state. The released energy is detected by the radiofrequency coils as the raw MR signals that go into images. The amount of released energy depends on the tissue property, thus MRI is able to create images of the anatomical brain structure to provide insight into the locations and distribution of different cerebral tissue types including gray matter, white matter, and cerebrospinal fluid. Over the past two decades, hundreds of structural MRI studies examining the neuroanatomical correlates of psychiatric disorders were conducted using voxel-based morphometry (VBM), a computational approach for characterizing group-level differences in regional volumes and tissue concentrations through voxel-wise comparison of brain images (Ashburner & Friston, 2000). In study 1 of my dissertation, VBM was used to assess associations between social affective benefit and brain gray matter volume.

However, this imaging method is limited because it fails to reveal immediate physiological changes related to the active brain functioning in a specific cognitive domain. In recent decades, functional MRI (fMRI) was introduced into neuroimaging studies to overcome this limitation by both localizing highly activated brain areas and characterizing brain activation patterns during specific cognitive processes. Functional MRI uses the blood-oxygen-level dependent (BOLD) contrast (Ogawa, Lee, Kay, & Tank, 1990) to map neural activity under particular task conditions by measuring the change in blood oxygenation, i.e., the hemodynamic response, associated with neuron energy consumption in active brain areas (Huettel, Song, & McCarthy, 2004). Specifically, when certain neurons are activated, blood delivers oxygen to them more efficiently than to inactive neurons. This leads to a change of relative levels of

oxygenated hemoglobin and deoxygenated hemoglobin in active brain areas that can be detected by MRI scanners because of their differential magnetic susceptibility. Here the BOLD contrast measures the differences in signal on T_2*(decay of transverse magnetization)-weighted images as a function of the amount of deoxygenated hemoglobin (Arthurs & Boniface, 2002). Although the BOLD contrast is an indirect measure of neuronal activity, it is one of the best tools to investigate brain function non-invasively, especially because it can generate whole-brain functional images with high spatial localization and fair time resolution (Logothetis, 2008).

Brain activation is studied with specific fMRI experimental designs. The earliest and simplest experimental design is blocked design. In blocked designs, the experimental stimuli and control stimuli are presented in alternating blocks using fixed time intervals (e.g., 20 seconds). The modelling of fMRI activation compares the experimental block to a control block using the logic of subtraction. Blocked designs are good at detecting activated brain areas, and can induce robust experimental effect because of maximized signal-to-noise ratio (Huettel et al., 2004). However, because the task conditions are extended in time, blocked designs are not able to capture the shape and timing of the hemodynamic response, which makes certain tasks inappropriate for blocked designs. In contrast, event-related designs demonstrate a better sensitivity to the shape and timing of the hemodynamic response. In event-related designs, discrete and short-duration events are presented in randomized order with jittered time intervals, thus minimizing the temporal correlations between trials (Huettel, 2012). Although simple event-related designs generally evoke smaller changes in the BOLD signals compared to blocked designs, more complex event-related designs (e.g., rapid event-related designs) can be optimized so that they can have strong detection power without sacrificing estimation efficiency (Birn, Cox, & Bandettini, 2002). In study 2 of my dissertation, an event-related design was employed for measuring brain activation during reward anticipation.

1.3.2 The neural basis of affective reactivity during social contact

During social interaction, individuals need to interpret other people's behavior, infer their emotions and intentions, and adapt actions and goals accordingly. Such social cognitions are supported by a neural circuit called the social brain that consists of the medial prefrontal cortex, the ACC, the inferior frontal gyrus, the temporoparietal junction, and the posterior superior temporal sulcus (Adolphs, 2009; Blakemore, 2008).

Within the social brain, the medial prefrontal cortex hosts important processes required for mentalizing and understanding social emotions (Moll & de Oliveira-Souza, 2007). The inferior frontal gyrus is involved in emotional judgement and top-down emotion recognition (Nakamura et al., 1999). The temporoparietal junction is involved in thinking about mental states (Saxe & Kanwisher, 2003). The posterior superior temporal sulcus is part of the mentalizing network of the brain and is involved in the detection of faces and eye gaze in humans, and generally in the identification of biological motion (Blakemore, 2008; Van Overwalle & Baetens, 2009). In my dissertation, I focused on the ACC given its role in integrating social information with emotional information during social interaction (Adolphs, 2009; Eisenberger, 2012; Feng, Luo, & Krueger, 2015; Singer et al., 2004) and its implication in social environmental risk and resilience factors for psychiatric disorders (Akdeniz et al., 2014b; Holz et al., 2020; Lederbogen et al., 2011).

Functionality of the ACC

The ACC is the frontal part of the cingulate cortex surrounding the anterior part of the corpus callosum. An early influential view dichotomized the ACC anatomically into dorsal-cognitive and ventral-affective components based upon cytoarchitecture and connectivity within the human brain (See **Figure 1.2**, Bush, Luu, & Posner, 2000). The dorsal ACC connects with the lateral prefrontal cortex, parietal cortex, and the motor system (Devinsky, Morrell, & Vogt, 1995), making it a key hub for cognitive functions including executive functions by integrating sensory information with response selection (Bush et al., 1999; Vogt, Finch, & Olson, 1992). Moreover, the dorsal ACC is also involved in conflict monitoring, complex motor control, error detection, salience detection, working memory, and reward-based decision making (Bush et al., 1999; Bush et al., 2002; Carter, Botvinick, & Cohen, 1999; Devinsky et al., 1995; Drevets & Raichle, 1998; Menon & Uddin, 2010; Vogt et al., 1992). Meanwhile, the ventral ACC maintains strong reciprocal interconnections with the amygdala, nucleus accumbens, hypothalamus, hippocampus, anterior insula, and orbitofrontal cortex (Devinsky et al., 1995). The ventral ACC was thus discussed as the affective subdivision because it plays a role in processing emotional information, and in regulating emotional responses (Devinsky et al., 1995; Drevets & Raichle, 1998; Vogt et al., 1992; Whalen et al., 1998). Despite the popularity of this traditional dorsal-cognitive vs. ventral-affective dichotomy, a wealth of recent research provides evidence for a new framework proposing that both subdivisions contribute to emotional processing (Etkin, Egner, & Kalisch, 2011). In this

framework, the dorsal ACC is essential for the appraisal of emotion expression, while the ventral ACC regulates the emotional responses together with other limbic regions like the amygdala (Etkin et al., 2011). This framework is also supported by evidence showing strong connections between the dorsal and ventral ACC both during resting state (Margulies et al., 2007) and social stress (Akdeniz et al., 2014b).

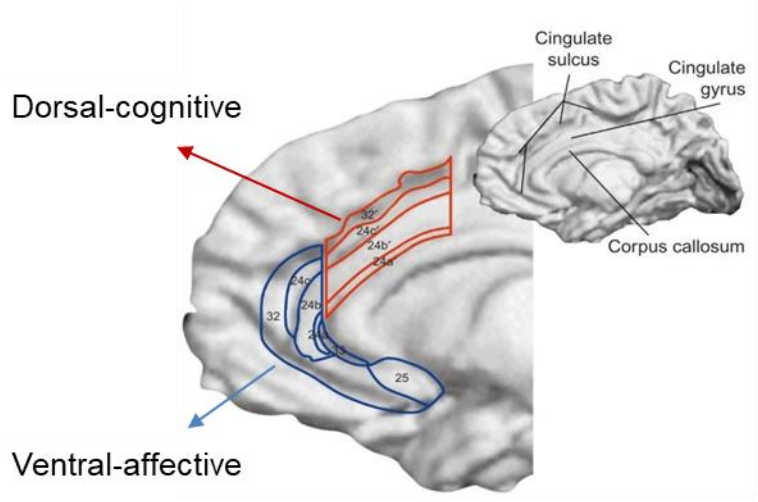

Figure 1.2. Anterior cingulate cortex (ACC) anatomy. The left enlarged part illustrates the schematic representation of cytoarchitectural areas of ACC. Numbers indicate Brodmann areas. The upper right part of the figure displays the medial surface of the right brain hemisphere (anterior towards the left, posterior towards the right) based on reconstructed MRI, which shows the localization of the cingulate gyrus relative to the corpus callosum. The figure was adapted from Bush et al. (2000).

The potential role of the ACC for social affective benefit

The ACC plays a pivotal role in processing the affective experience during social interactions. Eisenberger and colleagues (2012) have argued in their review article that the dorsal ACC was linked to the distress induced by social disconnection. For example, Eisenberger et al. (2007) reported that more pronounced social support in daily life, indicated by closer, more comforting, and more supportive social interactions in daily life, was linked to reduced dorsal ACC responses to social exclusion. The authors proposed that this association between reduced dorsal ACC responses in social situations and daily life social support may indicate a buffering effect on the neuroendocrine stress response, a well-established risk phenotype for many psychiatric disorders (Eisenberger et al., 2007). In a meta-analysis of fMRI studies in which participants were engaged in the ultimatum game, the dorsal ACC was activated when processing negative emotions related to unfair behavior (Feng et al., 2015). Moreover, the dorsal ACC was involved when observing partners experiencing

physical pain (Singer et al., 2004). This combined evidence suggests that the dorsal ACC is implicated in affective reactivity to social situations. On the other hand, the perigenual ACC located in the ventral-affective part of the ACC, has been discussed as a neural convergence site for social environmental risk factors such as urban upbringing (Lederbogen et al., 2011), low socioeconomic status (Gianaros et al., 2007), a migration background (Akdeniz et al., 2014b), and unstable social hierarchies (Zink et al., 2008). Perigenual ACC was also discussed as a central place subserving social resilience resources for mental health (Holz et al., 2020; Meyer-Lindenberg & Tost, 2012; Tost, Champagne, & Meyer-Lindenberg, 2015).

Taken together, these data suggest a strong relationship between the dorsal ACC and affective reactivity in social situations, and the perigenual ACC and social environmental risk and resilience factors. While there is sound evidence that the dorsal ACC and perigenual ACC map to social functions and social environmental risk and resilience measures, none of the above studies assessed the effects of daily-life social affective benefit on ACC structural integrity. In study 1, I therefore examined the association between the ACC structural integrity and daily-life social affective benefit.

1.3.3 The neural basis of affective reactivity to positive events

Real-life affective reactivity to positive events reflects how a person responds emotionally to positive experiences. This concept has been linked to reward sensitivity (Dornbach-Bender et al., 2020; Hundt et al., 2013). Thus, affective reactivity to positive events likely maps to the brain reward system.

The ventral striatum within the brain reward system and its relationship with psychiatric disorders

Reward is the attractive and motivational property of a stimulus, object, or event that induces approach, appetitive, and consummatory behaviors. For animals, reward cognition serves to increase the chance of survival and reproduction by learning the association between external stimuli or their own actions and appetitive outcomes, inducing approach-related behavior and triggering positive emotions (Schultz, 2015). The primary brain circuit underlying reward processing is the mesolimbic dopaminergic reward pathway that includes dopaminergic projections from the ventral tegmental area (VTA) to the ventral striatum (VS, see **Figure 1.3**, Arias-Carrion, Stamelou, Murillo-Rodriguez, Menendez-Gonzalez, & Poppel, 2010). Among others, the dopamine neurotransmission from VTA to VS regulates the incentive salience of stimuli

(e.g., "wanting" or "desire" for rewarding stimuli), reinforcement learning, motivational processing, and the perception of pleasure (Delgado, 2007).

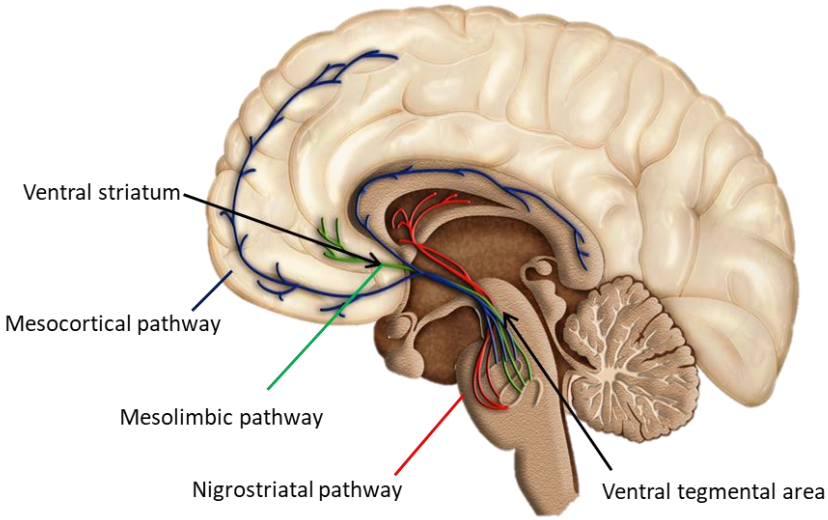

Figure 1.3. The mesolimbic dopaminergic pathway and its positioning in relation to the other dopaminergic pathways. The figure was adapted from Arias-Carrion et al. (2010).

The normal functioning of the mesolimbic dopaminergic pathway is vital for processing reward information in everyday life, whereas disturbance of the brain reward system functioning facilitates the development of various psychiatric disorders. Specifically, reduced VS reactivity during reward processing has been consistently reported in patients with mood disorders such as depression (Keren et al., 2018; Pizzagalli et al., 2009; Zhang, Chang, Guo, Zhang, & Wang, 2013) and bipolar disorder (Schwarz et al., 2020), schizophrenia spectrum disorder (Esslinger et al., 2012; Radua et al., 2015; Schwarz et al., 2020), autism (Dichter et al., 2012; Schwarz et al., 2020), attention-deficit/hyperactivity disorder (Scheres, Milham, Knutson, & Castellanos, 2007), and addiction (Hagele et al., 2015). There are however conflicting findings showing VS hyperactivation during reward processing in bipolar disorder patients (Nusslock et al., 2012). The attenuated reward-related VS reactivity has further been associated with more pronounced dimensional symptoms such as anhedonia (Arrondo et al., 2015; Schwarz et al., 2020), depressed mood (Arrondo et al., 2015; Hagele et al., 2015; Satterthwaite et al., 2015; Schwarz et al., 2020), or psychotic symptoms (Nielsen et al., 2012) exhibited in different neuropsychiatric conditions. Taken together, these findings suggest that VS hypoactivation during reward processing represents a well-established neural phenotype for psychiatric disorders.

Association between striatal reward processing and reward-related experiences in real life

Previous cross-sectional studies have shown a positive association between striatal reward-related functioning and various real-life measures of reward-related experiences (Forbes et al., 2009; Forbes et al., 2010; Heller et al., 2015; Kasanova et al., 2017; Kasanova et al., 2018a; Moran, Culbreth, Kandala, & Barch, 2019), but not with affective reactivity to positive events thus far. For instance, VS reactivity during reward anticipation was shown to be significantly related to daily-life positive affect in both depressed adolescents and in healthy controls (Forbes et al., 2009; Forbes et al., 2010), and to daily reports of anticipation and momentary enjoyment of anticipated pleasant events in schizophrenia patients (Moran et al., 2019). Moreover, the sustained VS engagement during reward processing positively predicted the duration of real-life positive emotional responses following a reward in the general population (Heller et al., 2015). Also, reward-oriented behavior (here, the tendency to be engaged in an activity if it was previously considered enjoyable) in daily life was related to the extent of reward-induced dopamine release in the VS in healthy adults and first-degree relatives of psychosis patients (Kasanova et al., 2017; Kasanova et al., 2018a). While using different reward-related daily-life experiences and striatal reward-related measures, these studies suggest that established reward processing paradigms in the laboratory capture brain activity relevant to real-world reward-related experiences.

In study 2, I hereby examined the association between real-life affective reactivity to positive events and VS reactivity during reward anticipation, two well-established phenotypes that have not been directly associated yet and that are related to vulnerability for psychiatric disorders. Importantly, previous studies have shown a significant developmental effect on striatal reward processing in the early life span from adolescence to early adulthood (Braams, van Duijvenvoorde, Peper, & Crone, 2015; Schreuders, Braams, Crone, & Guroglu, 2021). I thus employed an accelerated longitudinal design with three measurement time points to assess whether a potential association between real-life affective reactivity to positive events and VS reactivity changes over the course of three measurement time points, and to track and control for the developmental changes of striatal reward processing.

1.4 Research objectives

Previous ambulatory assessment studies identified social affective benefit and affective reactivity to positive events as two significant resilience measures for daily-life affective well-being, but until today the neural bases of these real-life resilience measures are unknown. To address this gap in the literature, I assessed the neural bases of social affective benefit (study 1) and affective reactivity to positive events (study 2) separately in a partly overlapping community-based cohort. Additionally, I explored the relevance of these real-life affective resilience measures for psychiatric risk and resilience.

In study 1, I assessed daily-life affective well-being using the MDBF affective valence scale, social contact information with ambulatory assessment, and acquired structural MRI data in a large community-based sample of healthy adults. I aimed to 1) test the robustness of social affective benefit in real life in two independent samples , 2) examine the association between social affective benefit and ACC gray matter volume, and 3) explore the relevance of social affective benefit for social and psychiatric resilience measures assessed using self-report scales. I hypothesized that: (a) social contact is associated with increased affective valence in real life. This hypothesis was first tested in a discovery sample (n=100), and then validated in a replication sample (n=177) using multilevel modeling; (b) individual differences in social affective benefit are positively associated with differences in ACC gray matter volume. I derived this hypothesis from the strong relationship between the ACC, social behavior and social environmental risk and resilience for psychiatric disorders suggested by the existing literature, and addressed this question by computing multiple regression models in imaging space; (c) individual social affective benefit is associated with measures of social psychiatric resilience.

In study 2, I assessed affective well-being using the positive affect scale, tracked the intensity of positive events in daily life using ambulatory assessment, and collected fMRI data using a well-established reward processing paradigm, i.e., the monetary incentive delay (MID) task (Kirsch et al., 2003). This was done in an accelerated longitudinal study design with three measurement time points including adolescents and young adults. I attempted to 1) test the robustness of the affective reactivity to positive events in daily life, 2) examine the association between striatal reward processing and affective reactivity to positive events at the between-subject level at

baseline, and then at the within-subject level across three measurement time points using multilevel models, 3) explore the influences of psychological and social environmental risk and resilience measures on the within-subject relationship between striatal reward processing and real-life affective reactivity to positive events. Additionally, I tested for age-related effects reflecting a previously reported developmental change in striatal reward functioning from adolescence to early adulthood (Braams et al., 2015; Schreuders et al., 2021). I hypothesized that: (a) positive event intensity is associated with increased positive affect in real life. This hypothesis was first tested in a sample (n=105) comprising adolescents and adults with baseline data (T1), which was then validated by second wave (T2) and third wave data (T3) using three separate multilevel models; (b) higher affective reactivity to positive events is associated with increased VS reactivity during reward anticipation. I first tested this hypothesis at the between-subject level by computing multiple regression models in imaging space with T1 data, then at the within-subject level by building multilevel models including data from all three measurement time points; (c) the relationship between affective reactivity to positive events and VS reactivity during reward anticipation was moderated by psychological and social environmental risk and resilience measures, given that these two measures have been related to the development of psychiatric disorders previously (Arrondo et al., 2015; Bylsma et al., 2011; Khazanov et al., 2019; Peeters et al., 2003; Radua et al., 2015; Schwarz et al., 2020).

Please note that several parts of this dissertation have already been published or are about to be published by the doctoral candidate as a (shared) first author. Therefore, certain sections, tables, or figures of this dissertation will be identical to the following publications:

Gan, G.*, **Ma, R.***, Reichert, M., Giurgiu M., Ebner-Priemer, U., Meyer-Lindenberg, A.*, Tost, H.* Neural structural correlates of affective benefit from real-life social contact. *JAMA Psychiatry*. doi:10.1001/jamapsychiatry.2021.0560. ***These authors contributed equally.***

Ma, R.*, Gan, G.*, Reichert, M., Giurgiu M., Reinhard, I., Moessnang, C., Schwarz, K., Berhe, O., Braun, U., Ebner-Priemer, U. W., Meyer-Lindenberg, A.*, Tost, H.* Longitudinal association between neural and real-life reward processing and the

influence of social environmental risk for psychiatric disorders. *In preparation*. ***These authors contributed equally.***

2 STUDY 1: NEURAL CORRELATES OF AFFECTIVE BENEFIT FROM REAL-LIFE SOCIAL CONTACT AND IMPLICATIONS FOR PSYCHIATRIC RESILIENCE

2.1 Abstract

Social support is a strong predictor of mental health. In daily life, social contact has been shown to impact mental well-being in healthy and psychiatric populations, while loneliness strongly increases morbidity and mortality. Despite these clear and medically relevant observations, the neural mechanisms underlying real-life “social affective benefit” and its implications for psychiatric resilience are unknown. Thus we aimed to investigate the impact of real-life social contact on affect and brain structure using ambulatory assessments, structural magnetic resonance imaging (MRI), and measures of psychological and social risk and resilience for psychiatric disorders. Discovery sample (n=100) and replication sample (n=177) reported repeatedly on social contact and affective valence across one week in daily life using smartphone-based electronic diaries, and completed a battery of social and psychological risk and resilience measures for psychiatric disorders. The replication sample additionally underwent structural MRI at the Central Institute of Mental Health Mannheim. Results showed that real-life social contact significantly increased affective valence in the discovery and replication samples. Individuals with higher social affective benefit showed significantly increased gray matter volume in the anterior cingulate cortex and higher social competence factor scores including measures of psychiatric resilience. Our findings identify a neural substrate for a core outcome of human real-life social interaction and demonstrate a link between social affective benefit and an emotion and stress regulatory brain region implicated in epidemiological risk and resilience for psychiatric disorders. Our findings also provide a rationale for strategies targeting psychiatric social dysfunction and the capacity for efficient utilization of social support in preventing and treating vulnerable individuals and psychiatric patients with severe social impairments.

2.2 Introduction

A supportive social network is a well-validated protective factor for physical and mental health (Hefner & Eisenberg, 2009; Holz et al., 2020; Victor & Yang, 2012), whereas loneliness and poor social ties strongly increase all-cause mortality (Holt-Lunstad et al., 2010; Rico-Uribe et al., 2018) and psychiatric morbidity (Beutel et al., 2017; Cacioppo et al., 2006). People seek social contact, likely because being together with other people increases their well-being and buffers the effects of adverse everyday experiences such as negative emotions and stress (Cohen & Wills, 1985; Mitchell et al., 1982), which confer risk for mental health. By measuring mental well-being in people's natural environment, ambulatory assessment studies demonstrated that real-life social contact is associated with mental well-being indicated by an increase in positive affect (Brown et al., 2007; Kasanova, Oorschot, & Myin-Germeys, 2018b; Oorschot et al., 2013) or a decrease in negative affect (Brown et al., 2007; Husky et al., 2004; Kwapil et al., 2009; Oorschot et al., 2013). Affect during social interaction has further been shown to be modulated by how close the participants felt to the social contact (Brown et al., 2007; Kwapil et al., 2009). Surprisingly, while the so-called "social brain" (Adolphs, 2009; Van Overwalle, 2009) has been studied extensively in psychiatric neuroscience, the neural basis of the fundamental human experience of benefiting emotionally from real-life social contact has received little attention in psychiatric neuroscience so far.

Within the social brain, the anterior cingulate cortex (ACC) is a crucial node for social environmental risk and resilience (Holz et al., 2020; Meyer-Lindenberg & Tost, 2012; Tost et al., 2015), and has a regulatory function in integrating emotions with behavior (Adolphs, 2009; Etkin et al., 2011; Laird et al., 2011; Vogt, 2005). The ACC has been related to disturbed emotion regulation and stress-related psychiatric disorders (Yucel et al., 2003) as well as social environmental risk and resilience factors for mental health such as social network size (Bickart, Wright, Dautoff, Dickerson, & Barrett, 2011; Lewis, Rezaie, Brown, Roberts, & Dunbar, 2011), perceived social standing (Gianaros et al., 2007), urban upbringing (Haddad et al., 2015; Lederbogen et al., 2011), and ethnic minority status (Akdeniz, Tost, & Meyer-Lindenberg, 2014a; Akdeniz et al., 2014b). Moreover, the ACC plays a pivotal role in modulating the affective experience during social interactions. For example, the ACC has been implicated in integrating negative emotions with social pain induced by social rejection (Eisenberger, 2012;

Eisenberger et al., 2007), observing loved ones experience physical pain (Singer et al., 2004), and unfair behavior (Feng et al., 2015). Altered ACC activation and connectivity has further been linked to unstable social hierarchies (Zink et al., 2008), as well as neuropeptides implicated in social behavior such as genetic variation in the oxytocin receptor gene (Tost et al., 2010) and vasopressin administration (Zink, Stein, Kempf, Hakimi, & Meyer-Lindenberg, 2010). Given its central role in the salience network (Menon & Uddin, 2010; Seeley et al., 2007), the ACC may specifically contribute to the rapid identification of behaviorally relevant social signals during social contact (Adolphs, 2009). These human data are supported by work in non-human species. In macaques, the ACC is highly connected with social cognition networks (Apps, Rushworth, & Chang, 2016). In particular, the ACC gyrus may be important for "processing the costs and benefits of acting in social context" (Apps et al., 2016). These data suggest a strong relationship between the affective benefit from social contact, social environmental risk and resilience for mental health, and the integrity of the ACC.

Despite the fundamental importance of social factors for mental health, it is unclear which brain circuits underlie the affective quality of social contact in real life. To this end, we combined methods from epidemiology, psychology, and neuroimaging to study the effect of social contact on affective well-being in daily life using ambulatory assessment, an established method for measuring dynamic variations in affect using smartphone-based electronic diaries (e-diary) (Tost et al., 2019; Trull & Ebner-Priemer, 2014). We were specifically interested in whether real-life social affective benefit, quantified as the direction and degree to which an individuals' momentary affective valence is influenced by social contact, relates to ACC gray matter volume as measured by structural magnetic resonance imaging (MRI). Furthermore, to assess the relevance of real-life social affective benefit for psychiatric risk and resilience, we assessed social psychological measures including personality traits (e.g., neuroticism, agreeableness), loneliness, well-being, and coping strategies in stressful life situations using established inventories. We hypothesized that: (a) social contact increases affective valence in real life. This hypothesis was first tested in a discovery sample (n=100) and validated in a replication sample (n=177) using multilevel modeling. We further probed the robustness of this effect in supplementary models with alternative covariate definitions; (b) Individual differences in social affective benefit are associated with differences in ACC volume. We derived this hypothesis from the strong relationship between the ACC, social behavior and social environmental risk and

resilience for psychiatric disorders suggested by the existing literature, and addressed this question by computing multiple regression models in imaging space; (c) Individual social affective benefit is associated with measures of social psychiatric resilience.

2.3 Methods

2.3.1 Participants

343 healthy young adults were recruited between September 1, 2014, and November 31, 2019, as part of a representative community-based sample within the framework of the Psychoepidemiological Center at the Central Institute of Mental Health (CIMH) in Mannheim, Germany. All participants were randomly drawn from the local population registries of communities located in the Rhine-Neckar region in Germany based on a two-stage proportionally layered procedure taking into account specific population stratifications such as age, sex, and nationality. All participants took part in a 7-day ambulatory assessment protocol including smartphone-based e-diary assessments, GPS-based location tracking, as well as accelerometry, and completed a standard battery of socio-demographic and social and psychological inventories (Reichert et al., 2017; Tost et al., 2019). Of those 343 participants, 211 additionally underwent structural MRI at the end of the study week after returning the smartphones. General exclusion criteria included a history of a significant general medical or neurological disorder. For MRI, standard MRI exclusion criteria were applied (e.g., metal implants, pregnancy). Participants were further excluded from data analysis if they endorsed a current or lifetime psychiatric disorder (e.g., major depression, anxiety disorder) as determined by the Mini-DIPS (Margraf, 1994) or the SCID-IV interview (First, Spitzer, Gibbon, & Williams, 2001). For the discovery study, comprised of only the ambulatory assessment part, we included 100 out of 132 participants in the final sample (reasons for exclusion: n = 27, potential psychological problems; n = 5, < 10 data points for either the alone or in company condition). For the replication study, comprised of the ambulatory assessment and MRI part, we included 177 out of 211 participants in the final sample (reasons for exclusion: n = 12, potential psychological problems; n = 1, potential psychological problems and major structural abnormalities; n = 1, major structural abnormalities; n = 2, potential multiple sclerosis; n = 2, e-diary compliance < 30%; n = 1, interval between ambulatory assessment and MRI > 300 days (mean ± SD: 2.59 ± 10.83 days); n = 15, < 10 data points for either the alone or in company condition).

The Medical Ethics Committee II of the Medical Faculty Mannheim at Heidelberg University, Germany, approved this study. All participants provided written informed consent before study participation and received monetary compensation.

2.3.2 Ambulatory assessment setup and data analysis

Hardware and e-diary sampling:

Participants carried a smartphone (Motorola Moto G, Motorola Mobility LLC, Libertyville, Illinois, USA, www.motorola.com) and an accelerometer that was attached to the hip (movisens Move-II or movisens Move-III, movisens GmbH, Germany, http://www.movisens.com) for seven consecutive days in their natural environment. They responded to 9-23 possible prompts every day (12.3 on average ± 1.6 SD) between 7:30 to 22:30 including 2 fixed time-based prompts at 8:00 and 22:20. Additionally, a location-based trigger-algorithm continuously monitored the distance between the current and previous locations of the participants and triggered a prompt whenever the distance exceeded 500 meters (Reichert et al., 2017; Tost et al., 2019). Minimum and maximum time intervals between prompts were set to 40 and 100 minutes, respectively. Participants could postpone each prompt for five to 15 minutes. For the implementation of the e-diaries and sampling strategy, we used the ambulatory assessment software movisensXS, version 0.6.3658 (movisens GmbH, Germany, https://xs.movisens.com).

Affective valence items:

We assessed momentary affective valence using a well-established two-item scale for affective valence (Wilhelm & Schoebi, 2007) that has been widely used for measuring daily-life fluctuations in mood with ambulatory assessments (Giurgiu et al., 2019; Reichert et al., 2017; Tost et al., 2019). It consists of the bipolar items “content” – “discontent” (German translation: “zufrieden” – “unzufrieden”) and “unwell” – “well” (German translation: “unwohl” – “wohl”) that are presented in reversed polarity at the edges of two computerized visual analog scales with a score range from 0 to 100 (**Figure 2.1**). Consistent with previous work (Wilhelm & Schoebi, 2007), the psychometric property of this scale in our study was good (within-subject reliability coefficient: 0.74). The scores of the two valence items for every prompt were rectified, averaged, and entered as the outcome variable in our multilevel models. Regarding potential ceiling effects of the scale, **Figure 2.2** provides a good illustration of the

distribution of our data: consistent with other healthy samples (Giurgiu et al., 2019), the average valence levels (intercept beta) were 71 (discovery sample; SE = 7.9) and 67 (replication sample; SE = 7.5) of 100, respectively, and even the individuals with the overall highest valence ratings (> 90: 5 out of 277 persons) showed individual positive effects of social contact on affective valence in both samples (thin gray lines in **Figure 2.2A and 2.2B**). We additionally repeated all analyses after excluding the five individuals with valence ratings above 90, which did not influence any of the reported findings. We thus conclude that the reported results are not explained by potential ceiling effects.

Social contact items:

To assess momentary social contact (Brown et al., 2007; Husky et al., 2004; Kasanova et al., 2018b; Kwapil et al., 2009; Oorschot et al., 2013), another item asked the participants to indicate whether they were alone or in the company of others at each prompt (level 1 predictor in our multilevel models). In the case of social contact, participants additionally rated the liking of the company on a visual analog scale with a sliding locator ("I do not like the company" (Collip et al., 2011), range 0 to 100). **Figure 2.1** illustrates the e-diary items. Notably, the SAB effects reported in this study were also significant in supplemental analyses considering only "in company"-events with positively rated social contacts (i.e., "I do not like the company" ≤ 50), which was the case for most events (replication sample: 95.3%; discovery sample: 93.8%).

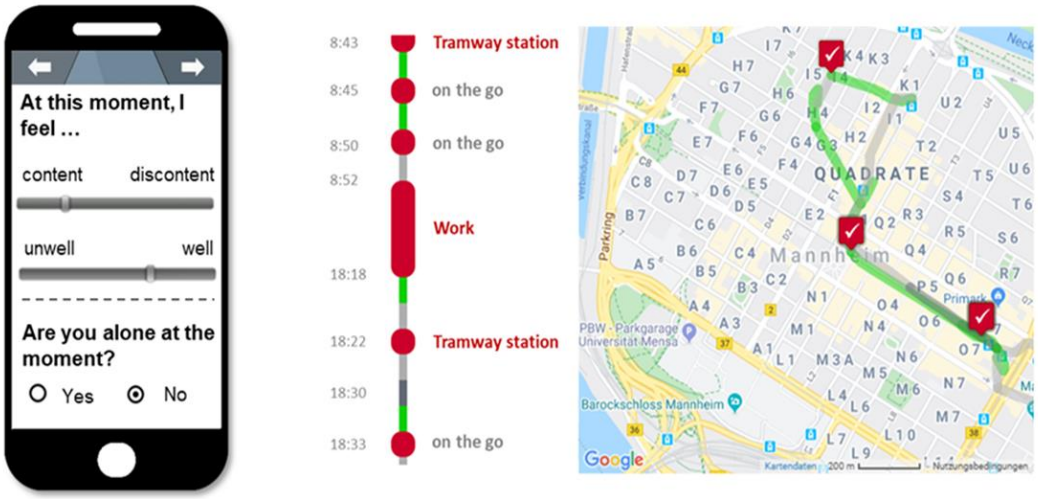

Figure 2.1. Ambulatory assessment, daily life location tracking. Valence and social contact e-diary items (for illustrative purposes shown on a single screen; left panel). Location tracking and labeling of stationary whereabouts for an exemplary study day (right panel).

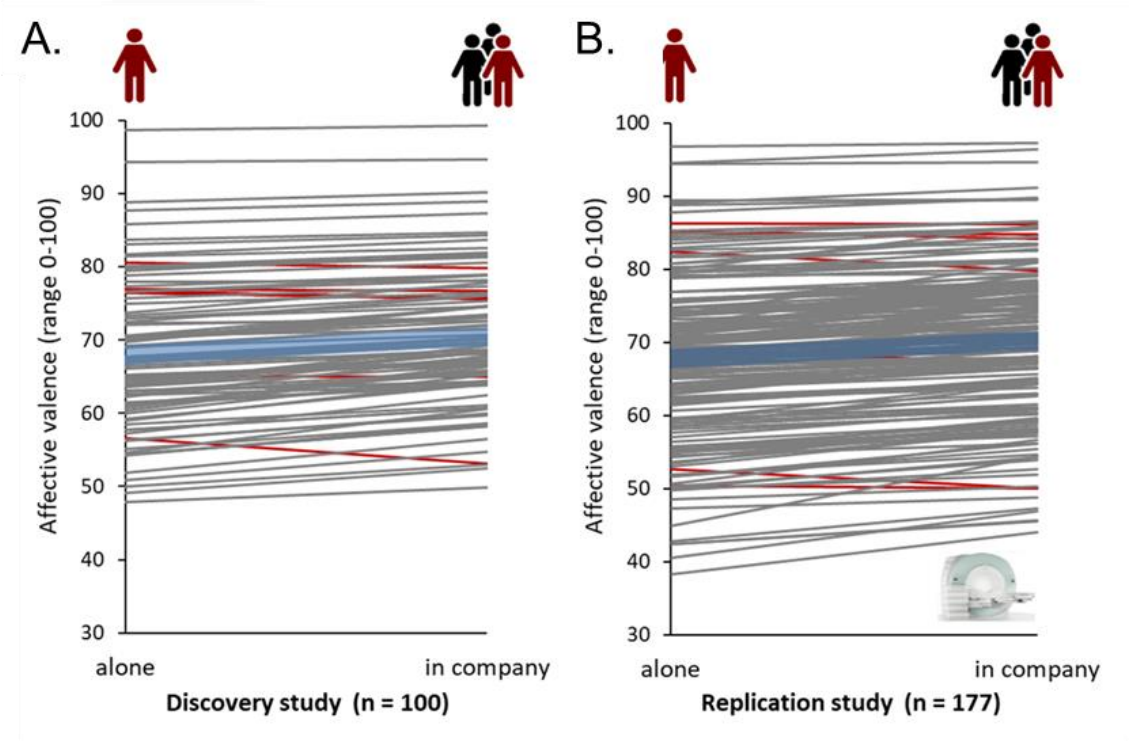

Figure 2.2. Individual and group social affective benefit effects for **A.** the discovery and **B.** the replication sample. Slopes depict the degree to which each participant's affective valence (y-axis) was influenced by being in company versus being alone (x-axis). Random effects of the multilevel model, the degree to which each participant's affective valence (y-axis) was influenced by being in company versus being alone (x-axis), relative to the multilevel model fixed group effect (thick blue line), is depicted with thin gray (positive social affective benefit effects) and thin red (negative social affective benefit effects) lines.

Multilevel modeling:

We estimated the effect of social contact (dichotomous rating: 0 = alone; 1 = in company) on affective valence by conducting random-intercept random-slope multilevel model analyses in SAS (version 9.4., SAS Institute Inc., Cary, NC, USA), thereby nesting e-diary assessments (level 1) within participants (level 2) (Bolger & Laurenceau, 2013). Besides our main predictor of social contact, we added the level-1 predictors time of the day and time of the day squared (transformed to the daily study start time at 7:30 AM) to the multilevel model to control for time-of-day effects on affective valence (Reichert et al., 2017; Tost et al., 2019). We added sex and age as level-2 covariates. Following established procedures (Bolger & Laurenceau, 2013), we incorporated random effects for both the intercept and each predictor, and subsequently deleted non-significant random effects (e.g., for time-squared). Equation 2.1 details the full model below using a single equation representation.

Equation 2.1:

$$Y(\boldsymbol{affective\ valence})_{ij} = \beta_{00} + \beta_{01} * age_j + \beta_{02} * sex_j + \beta_{10} * \boldsymbol{social\ contact}_{ij} + \beta_{20} * time\ of\ day_{ij} + \beta_{30} * time\ of\ day_{ij}^2 + u_{0j} + u_{1j} * social\ contact_{ij} + u_{2j} * time\ of\ day_{ij} + r_{ij}$$

Y_{ij} represents the level of affective valence in person *j* at the time *i*. Within-subject effects are modeled on level 1, represented by each participant's (subscript *j*) value entries for every prompt (subscript *i*). On level 2, between-subject effects are estimated for age and sex. Beta coefficients denote the intercept, the effect of our main predictor social contact, and the effects of the level-1 covariates (time of the day, time of the day squared). Random effects, i.e., individual variation around the sample mean, are represented by u_{ij}. Inspection confirmed that level-1 residuals (see **Figure S2.1**) did not deviate from the normal distribution, which suggests that our multilevel model was well suited to handle the data structure.

Multilevel model estimates reflecting individual social affective benefit:

In the model detailed above, individual SAB, or the degree to which a given person profits in affective valence from social contact, is reflected by the random effects of social contact ($u_{1j} * \text{social contact}_{ij}$) on affective valence. It reflects the person-specific deviation from the fixed group effect of the social contact predictor ($\beta_{10} * \text{social contact}_{ij}$) on the affective valence outcome. We used the estimates for the random effects of social contact for each person to assess associations with ACC gray matter volume in neuroimaging space and with factor scores of inventory-based social and psychological risk and resilience measures computed by principal component analysis (PCA), respectively.

Robustness of the social affective benefit effect:

To check the robustness of the social affective benefit effect, we tested for the social affective benefit effect in the discovery and replication samples. We also conducted several supplementary multilevel analyses. First, we included additional potential confounders such as physical activity (centered on the subjects' mean; for details on assessment and preprocessing refer to (Reichert et al., 2017; Reichert et al., 2016)) and situational context (categorized as: at work, leisure, and others (Tost et al., 2019))

as level-1 predictors, as well as neuroticism as a level-2 predictor in the multilevel model (**Table S2.1**) because these factors have previously been shown to influence affective valence in daily life (Reichert et al., 2017; Tost et al., 2019). The situational context was labeled (e.g., at work, leisure, other) retrospectively by participants for locations where they stayed statically for five or more minutes throughout the study week (see **Figure 2.1, right panel**) using a procedure corresponding to the Day Reconstruction Method (Kahneman, Krueger, Schkade, Schwarz, & Stone, 2004) implemented in the Geocoder software (movisens GmbH, Germany, http://www.movisens.com). Then, given that affective valence might be influenced by the quality of social contact, we recomputed the main multilevel model while only considering positively rated social contacts (i.e., “I do not like the company ≤ 50”) (**Table S2.1**). Graphical inspection confirmed that the level-1 residuals did not seriously deviate from normal distribution providing evidence that our multilevel model is well suited for the given data structure in this large sample (**Figure S2.1**).

2.3.3 Socio-demographic and psychological measures

Participants completed an online questionnaire battery including basic socio-demographic measures which were used to compute an established multidimensional aggregated index of socio-economic status (SES) (Lampert, Kroll, Müters, & Stolzenberg, 2013). Additionally, participants reported on social and psychological risk and resilience measures indicating well-being (WHO-5) (Krieger et al., 2014), satisfaction with life (SWLS) (Glaesmer, Grande, Braehler, & Roth, 2011), personality traits including neuroticism, extraversion, openness, agreeableness, conscientiousness (NEO-FFI) (Borkenau & Ostendorf, 2008), trait anxiety (STAI-T) (Laux, Glanzmann, Schaffner, & Spielberger, 1981), schizotypal personality traits (SPQ-brief) (Raine & Benishay, 1995), loneliness (UCLA) (Döring & Bortz, 1993; Russell, Peplau, & Cutrona, 1980), self-efficacy (SWE) (Jerusalem & Schwarzer, 1992), sense of coherence (SOC) (Hannöver et al., 2004), and optimism (LOT-R) (Carver, Scheier, & Segerstrom, 2010; Herzberg, Glaesmer, & Hoyer, 2006; Scheier, Carver, & Bridges, 1994). Participants were also asked to report on coping strategies in previously "stressful" situations using the brief-COPE (Carver, 1997; Knoll, Rieckmann, & Schwarzer, 2005) (subscales: active coping, positive coping, social support, and negation; derived from a second-order PCA (see **Table S2.2 in** supplemental content)). Additionally, the social network size and social network

complexity (i.e., membership of different kinds of groups) were assessed using the social network index (SNI) (Cohen, Doyle, Skoner, Rabin, & Gwaltney, 1997), a measure only available in the replication sample. **Table 2.1** displays the socio-demographic and psychological characteristics for both the discovery and replication samples.

Table 2.1. Socio-demographic and psychological characteristics for the discovery (n = 100) and the replication sample (n = 177).

	Discovery sample		**Replication sample**		**Test statistic**[b]	***p***
	mean ± SD[a]	n	mean ± SD	n		
Demographic data						
Age (years)	23.09 ± 3.08	100	22.96 ± 2.74	177	t = -0.37	0.72
Sex (females/males)	72/28	100	81/96	177	χ^2 = 17.79	**< 0.001**[d]
Education (years)	12 (6)[e]	100	12 (6)[e]	176	U = 8224	0.32
Socioeconomic status (SES, aggregate score)	14.42 ± 3.04	100	15.70 ± 3.16	176	t = -0.71	0.48
Psychological measures						
Well-being (WHO-5, %)	65.22 ± 15.44	98	64.28 ± 15.77	174	t = -0.48	0.63
Life satisfaction (SWLS, sum)	27.66 ± 4.78	100	27.45 ± 4.82	173	t = 0.36	0.72
Trait anxiety (STAI-T, sum)	35.00 ± 8.14	99	34.33 ± 7.88	174	t = 0.67	0.50
Personality (NEO-FFI-30)						
Extraversion (mean)	2.56 ± 0.55	100	2.58 ± 0.58	175	t = -0.38	0.71
Neuroticism (mean)	1.3 ± 0.62	100	1.13 ± 0.67	175	t = 2.03	**0.04**[d]
Openness (mean)	2.45 ± 0.75	100	2.47 ± 0.85	175	t = -0.23	0.82
Agreeableness (mean)	3.06 ± 0.61	100	2.61 ± 0.55	175	t = 6.3	**< 0.001**[d]
Conscientiousness (mean)	3.07 ± 0.55	100	3.02 ± 0.55	175	t = 0.73	0.47
Self-efficacy (SWE, sum)	30.21 ± 4.20	99	30.52 ± 3.95	174	t = -0.60	0.55
Coping (Brief COPE)[c]						
COPE-Social support (mean)	2.67 ± 0.67	99	2.56 ± 0.66	175	t = 1.26	0.21
COPE-Positive coping (mean)	2.49 ± 0.59	99	2.51 ± 0.56	175	t = -0.29	0.77
COPE-Negative coping (mean)	1.84 ± 0.42	99	1.83 ± 0.38	175	t = 0.17	0.86
COPE-Active coping (mean)	2.91 ± 0.58	99	2.99 ± 0.58	175	t = -1.14	0.26
Sense of coherence (SOC, sum)	149.99 ± 18.25	98	150.04 ± 18.50	175	t = -0.022	0.98
Optimism (LOT-R, sum)	16.62 ± 3.69	100	16.97 ± 3.48	175	t = -0.79	0.43
Social network index (SNI)						
Social network size	-	-	19.59 ± 8.54	175		
Social network complexity	-	-	5.54 ± 1.43	175		
Loneliness (UCLA, mean)	1.50 (2.80)[e]	100	1.5 (2.15)[e]	175	U = 8458	0.65

[a]SD = standard deviation. [b]Type of statistical test for between-sample comparisons: Normally distributed variables → independent t-tests, non-normally distributed variables → Mann-Whitney-U test, dichotomous variables → χ^2 test. [c]brief-COPE subscale means based on second-order PCA. [d]Please note: We controlled all analyses for the effects of sex. The addition of neuroticism and agreeableness as covariates to the respective models did not affect any of the reported findings. [e]Medians and ranges (in parenthesis) were reported for non-normally distributed variables.

2.3.4 Structural MRI data acquisition, preprocessing, and analysis

Structural scans were acquired on a 3T whole-body Siemens Magnetom Trio Tim MR scanner located at the CIMH using a T1-weighted 3D magnetization-prepared rapid acquisition gradient-echo (MPRAGE) sequence with whole-brain coverage and a spatial resolution of 1 mm^3 (MR parameters: repetition time = 2300 milliseconds (ms), echo time = 3.03 ms, inversion time = 900 ms, flip angle = 9°, 192 contiguous sagittal slices, slice thickness = 1 mm, field of view = 256 mm). Image quality and potential brain structural abnormalities were inspected by a medical doctor. Two participants were excluded because of major structural abnormalities.

For preprocessing and segmentation of structural scans, we used Voxel-Based Morphometry (VBM) implemented in the Computational Anatomy Toolbox (CAT, http://www.neuro.uni-jena.de/cat/index.html#VBM), which is based on Statistical Parametric Mapping (SPM12, Wellcome Department of Cognitive Neurology, London, www.fil.ion.ucl.ac.uk/spm) and runs in MATLAB (version R2013b, Mathworks, Massachusetts, USA). VBM is a fully automated, unbiased, whole-brain MRI analysis technique that allows estimating the voxel-wise composition of brain tissues such as gray matter, white matter, and cerebrospinal fluid (Ashburner & Friston, 2000). As part of the VBM toolbox pipeline, the structural scans were segmented into gray matter, white matter, and cerebro-spinal fluid tissue classes according to a priori tissue probability maps, spatially normalized to the Montreal Neurological Institute (MNI) space by linear and non-linear transformations using the Diffeomorphic Anatomical Registration through Exponentiated Lie algebra (DARTEL) template. In addition, the preprocessed gray matter maps were modulated with the Jacobian determinants by scaling with number of volume changes due to spatial normalization to correct for differences in head size. Additionally, we corrected the gray matter maps for bias-field inhomogeneities, cleaned up gray matter partitions, and applied a classical Markov

random field model, and spatial adaptive nonlocal means denoising using default parameters of the VBM toolbox. Finally, the noise-corrected, segmented, normalized, and modulated gray matter segments were smoothed with an 8 mm^3 full-width at half-maximum isotropic Gaussian kernel. Total intracranial volume (TIV) was computed for each participant for second-level analyses. Native T1 images as well as segmented, normalized and smoothed gray matter maps were visually inspected for scanner and motion artifacts.

To assess the effects of social affective benefit on gray matter volume, we entered individual social affective benefit effect values derived from the multilevel model (see **Figure 2.2B**) as the regressor of interest in a regression model in SPM12, thereby covarying for sex, age, and TIV. Significance was measured at $p < 0.05$ voxel-wise family-wise error (FWE) corrected within an *a priori* defined anatomical mask of the bilateral anterior cingulate cortex (ACC) from the Automated Anatomical Labeling (AAL) atlas (Tzourio-Mazoyer et al., 2002) that included the dorsal and perigenual aspects of the ACC. These subregions were of particular interest to this study since dorsal ACC and perigenual ACC receive overlapping cortical inputs (Beckmann, Johansen-Berg, & Rushworth, 2009; Tang et al., 2019), are functionally and structurally strongly interconnected (Beckmann et al., 2009; Johansen-Berg et al., 2008; Margulies et al., 2007) and have been linked to overlapping social functions (e.g., social affective reactivity (Eisenberger, 2012; Ochsner et al., 2006), pain induced by social rejection (Eisenberger, 2012; Eisenberger et al., 2007), reciprocal interaction (Feng et al., 2015; Tomlin et al., 2006), social valuation (Behrens, Hunt, Woolrich, & Rushworth, 2008), and social environmental risk and resilience factors such as perceived social standing, urban upbringing, and ethnic minority status (Akdeniz et al., 2014a; Akdeniz et al., 2014b; Gianaros et al., 2007; Haddad et al., 2015; Lederbogen et al., 2011; Margulies et al., 2007)). Outside the pre-hypothesized region ACC, we considered findings as significant if they passed a significance threshold of $p < 0.05$ FWE corrected for multiple comparisons across the whole brain.

2.3.5 PCA of social and psychological inventories

To quantify individual measures of social and psychological risk and resilience, we performed a PCA with varimax rotation in SPSS 22.0 (IBM) in 170 individuals of the replication sample, for which all necessary measures (see **Table 2.1**) were available.

2.4 Results

2.4.1 Real-life social contact robustly increased affective valence

Multilevel modeling revealed that social contact (i.e., alone vs. in company), our main predictor, significantly increased affective valence in the discovery sample (beta coefficient = 2.554, $p < 0.001$, see **Table 2.2**). Thus, as expected, our participants reported higher levels of affective valence when they were in the company of others compared to being alone in daily life. This social affective benefit effect was also highly significant in the replication sample (beta coefficient = 2.596, $p < 0.001$, see **Table 2.2**). For each participant included in the discovery and replication samples, we derived the individual social affective benefit effect from the random part of the multilevel model, which depicts the change in affective valence when individuals are in the company of others compared to being alone (see **Figure 2.2A/B**). Notably, supplementary analyses showed that the detected social affective benefit effect was robust against adding other potential confounders such as physical activity, situational context (i.e., at work, leisure, other), or neuroticism as covariates, measures that have been previously shown to influence affective valence (Kanning, 2012; Reichert et al., 2017; Tost et al., 2019) (see **Table S2.1**). The social affective benefit effect was also significant when we only considered “in company” events with positively rated social contacts (i.e., “I do not like the company” ≤ 50), which accounted for 95.3% (replication sample) and 93.8% (discovery sample) of events (see **Table S2.1**).

Table 2.2. Multilevel modeling of social affective benefit in the discovery and replication samples.

	Discovery sample (n = 100)				**Replication sample (n = 177)**			
Fixed effects								
Predictor	B	SE	*t* (df)	*p*	B	SE	*t* (df)	*p*
Intercept	71.012	7.877	9.01 (97)	**<0.001**	67.487	7.473	9.03 (174)	**<0.001**
Level-1 predictors								
Social contact: in company	2.554	0.578	4.42 (89)	**<0.001**	2.596	0.416	6.25 (168)	**<0.001**
Time (hours)	0.525	0.165	3.18 (3033)	**0.002**	0.645	0.118	5.49 (5012)	**<0.001**
Time-squared (hours^2)	-0.019	0.010	-1.86 (6965)	0.062	-0.020	0.007	-2.85 (12393)	**0.004**
Level-2 predictors								
Age (years)	-0.168	0.335	-0.50 (96)	0.618	-0.040	0.319	-0.12 (172)	0.901
Sex: female	2.751	2.305	1.19 (97)	0.236	2.097	1.754	1.20 (172)	0.234
Random effects								
Predictor	Variance estimate	SE	Wald-*Z*	*p*	Variance estimate	SE	Wald-*Z*	*p*
Intercept	92.39	15.270	6.05	**<0.001**	120.87	14.417	8.38	**<0.001**
Social contact	8.67	2.434	3.56	**<0.001**	8.71	1.646	5.29	**<0.001**
Time (hours)	0.206	0.054	3.81	**<0.001**	0.22	0.038	5.74	**<0.001**

Note: B, beta coefficient; SE, standard error; df, degree of freedom. Besides the main predictor social contact, level-1 predictors included time of day and time of day squared (transformed to the daily study start time: 7:30), and level-2 predictors included sex and age (see supplemental content for full equation). Non-significant random effects were deleted from the model (e.g., for time-squared).

2.4.2 Association between individual social affective benefit and brain structure

For the replication sample, the ROI-analysis within the ACC revealed that social affective benefit was positively associated with gray matter volume in the dorsal/perigenual ACC (x = 3, y = 33, z = 26; peak voxel $t = 3.92$, peak voxel $p_{FWE} = 0.016$, **Figure 2.3**). Thus, a larger social affective benefit was associated with larger gray matter volume in the ACC (**Figure 2.3**). No other brain area outside of the *a priori* ROI showed significant effects at a corrected whole-brain significance threshold ($p_{FWE} < 0.05$).

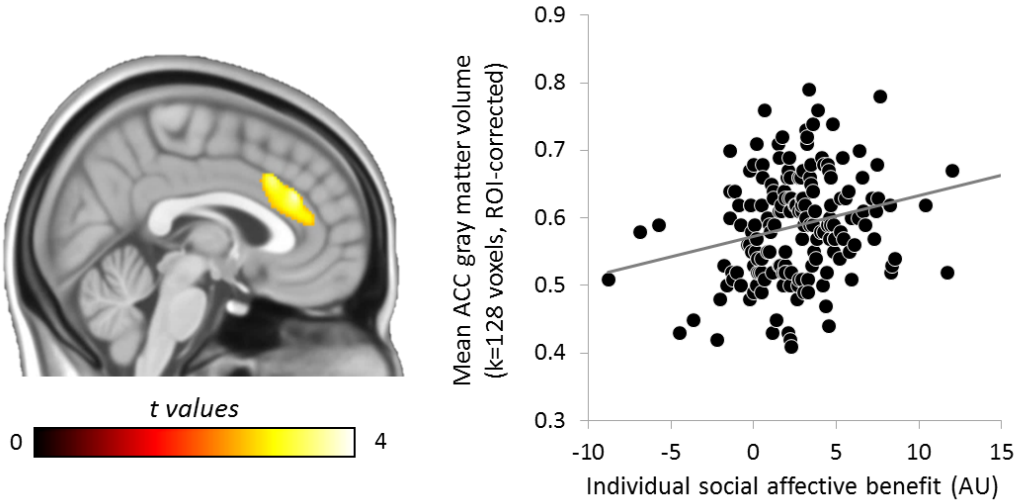

Figure 2.3. Association between individual social affective benefit effects and anterior cingulate cortex (ACC) gray matter volume. **a.** Brain map shows the positive association between individual social affective benefit effects (derived from the random part of the multilevel model) and individual ACC gray matter volume in the replication sample (*pFWE* = 0.016, ROI-corrected within the ACC), displayed at a threshold of $p < 0.005$ uncorrected across the whole brain for illustration purposes. Scatterplot displays the positive association between individual social affective benefit effects and mean values of ACC gray matter volume across voxels surviving FWE ROI-correction.

2.4.3 Association between individual social affective benefit, individual ACC gray matter volume, and social-psychological risk

Following the scree plot of the PCA analysis (**Figure S2.2**), we extracted three factors that explained 52.9% of the variance in the data. The PCA resulted in three social-psychological risk and resilience factors indicating *psychiatric risk* (highest factor loadings: trait anxiety, sense of coherence, neuroticism, satisfaction with life), *social competence* (including coping by proactively seeking social support, agreeableness, conscientiousness), and *other coping* in stressful situations (including positive reframing, active and negating coping strategies, openness) for the replication sample (n = 170 participants with complete social-psychological measures, see **Table 2.3**). The Kaiser-Meyer-Olkin measure of sampling adequacy was 0.84, and thus above the recommended minimum of 0.6 for exploratory PCAs. Bartlett's test of sphericity was significant ($\chi^2(136) = 1117.13$, $p < 0.001$), indicating that the social-psychological measures included in the PCA differed sufficiently from each other. Correlation

analyses revealed a significant positive correlation between the *social competence* factor scores and individual social affective benefit in daily life (Spearman's $r = 0.253$, $p = 0.001$; Pearson's $r = 0.250$, $p = 0.001$; Bonferroni-corrected p-threshold for 6 tests: $p < 0.008$; **Figure 2.4**). Social affective benefit did not correlate with the *psychiatric risk* factor scores or the *other coping* factor scores ($p > 0.16$). ACC gray matter volume did not correlate directly with any of the social psychological factor scores ($p > 0.52$).

Table 2.3: Factor loadings and communalities of social and psychological risk and resilience measures.

Measures	Factor 1: Psychological Risk	Factor 2: Social Competence	Factor 3: Other Coping	Communalities
Trait anxiety (STAI-T, sum score)	**-0.882**	-0.004	0.019	0.778
Sense of coherence (SOC, sum score)	**0.858**	0.104	0.007	0.747
Neuroticism (NEO, mean score)	**-0.776**	0.237	0.022	0.659
Satisfaction with life (SWLS, sum score)	**0.749**	0.226	0.063	0.616
Loneliness (UCLA, mean score)	**-0.688**	**-0.420**	0.021	0.650
Optimism (LOT-R, total score)	**0.647**	0.097	0.191	0.464
Well-being (WHO-5, percentage)	**0.644**	0.080	0.171	0.450
Self-efficacy (sum score)	**0.636**	-0.180	**0.446**	0.636
Extraversion (NEO, mean score)	**0.537**	**0.403**	0.078	0.457
Social network size (SNI)	0.327	0.193	-0.268	0.216
Coping - social support (brief-COPE, mean score)§	-0.010	**0.764**	0.178	0.616
Agreeableness (NEO, mean score)	-0.040	**0.701**	-0.028	0.494
Conscientiousness (NEO, mean score)	0.191	**0.555**	0.092	0.352
Coping - positive reframing (brief-COPE, mean score)§	0.176	-0.025	**0.732**	0.567
Coping - active (brief-COPE, mean score)§	0.191	0.335	**0.591**	0.499
Coping - negation (brief-COPE, mean score)§	**-0.483**	0.233	**0.531**	0.569
Openness (NEO, mean score)	0.029	0.057	**0.466**	0.221

Note: Values in bold represent factor loadings > .4. §brief-COPE factor composition based on second-order PCA, see **Table S2.2** for details.

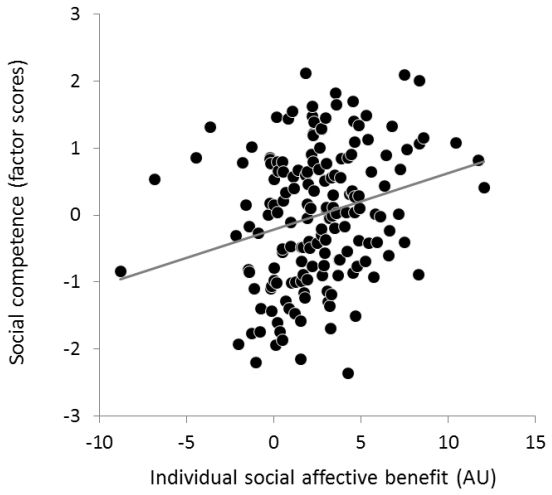

Figure 2.4. Individual social affective benefit effects correlate positively with the social competence factor scores (*Spearman's r* = 0.253, *p* = 0.001) as determined by a principal component analysis on social and psychological risk and resilience measures for psychiatric disorders.

2.5 Discussion

In this neuro-epidemiological study, we combined ambulatory assessment methods with structural MRI and questionnaire data to corroborate the affective benefit of real-life social contact, identify the underlying neural correlates, and probe the relevance of findings for mental health risk and resilience. Our data implicate a core region for emotional control in this fundamental resilience behavior.

First, as hypothesized, we show that social contact enhances affective valence in healthy individuals in real-life, as demonstrated in a discovery sample and replicated in a second, independent sample. The detected social affective benefit effect remained stable when we controlled for variables known to have a strong influence on daily affect such as neuroticism, physical activity, or situational context (Kanning, 2012; Reichert et al., 2017; Tost et al., 2019), which further underscores the robustness of our findings. The data extend prior studies demonstrating similar effects in psychiatric patients and individuals at increased psychiatric risk with social deficits such as social anxiety (Brown et al., 2007), social anhedonia (Brown et al., 2007; Kwapil et al., 2009), and schizotypal traits (Kasanova et al., 2018b; Oorschot et al., 2013). This suggests that although these individuals spent more time alone and/or prefer to be alone more often than healthy subjects (Brown et al., 2007; Kwapil et al., 2009; Oorschot et al., 2013), they enjoy being in the company of others (Brown et al., 2007; Kasanova et al., 2018b;

Oorschot et al., 2013) and profit in mental well-being from social contact (Brown et al., 2007; Husky et al., 2004; Kasanova et al., 2018b; Kwapil et al., 2009; Oorschot et al., 2013). Our findings in healthy community-based individuals are consistent with these data and corroborate the notion that social affective benefit is a fundamental human experience that can be robustly measured in real life. Our findings further suggest social affective benefit as a plausible resilience resource for everyday mental well-being. Moreover, our data draw attention to the potential value of smartphone-based preventative and therapeutic strategies aiming at fostering affective benefit in daily life and helping to establish, maintain and profit from everyday social relationships.

Second, our neuroimaging findings link higher levels of social affective benefit in daily life to higher brain gray matter volume in the ACC, a key node of the social brain that has been repeatedly implicated in the pathophysiology of stress-related mental disorders and discussed as a neural convergence site for social risk and resilience factors (Holz et al., 2020; Meyer-Lindenberg & Tost, 2012; Tost et al., 2015) such as social network size (Bickart et al., 2011; Lewis et al., 2011), perceived social standing (Gianaros et al., 2007), urban upbringing (Haddad et al., 2015; Lederbogen et al., 2011), and ethnic minority status (Akdeniz et al., 2014a; Akdeniz et al., 2014b). Notably, the ACC is an important subdivision of the social brain (Adolphs, 2009) supporting the integration of social emotional events and behavior (Apps et al., 2016; Vogt, 2005). This is plausibly relevant for daily-life social affective benefit since this behavioral experience requires the integration of social contexts and affective appraisals. For example, ACC activity has been associated with the effects of social support during adverse events such as pain administration to a spouse (Coan, Schaefer, & Davidson, 2006). Likewise, greater social support and diminished cortisol responses were associated with blunted stress-related activity in the dorsal ACC (Eisenberger et al., 2007). More generally, the central role in the salience network highlights the role of the dorsal ACC in detecting behaviorally relevant stimuli (Menon & Uddin, 2010; Seeley et al., 2007) such as social cues. Taken together, the existing evidence suggests that social environmental influences relevant to the risk architecture of psychiatric disorders map to a key node of a neural circuitry implicated in emotion regulation, social stress, and salience processing (Meyer-Lindenberg & Tost, 2012). Although our cross-sectional study design does not support causal inferences, we thus

speculate that larger ACC gray matter volumes support the ability to benefit emotionally from social contact in daily life.

Third, cross-validation of our ambulatory assessment data with social and psychological inventories of psychiatric risk and resilience showed that the individual propensity to benefit from social contact in daily life was specifically linked to a composite measure of social competence, as indicated by the ability to seek social support in stressful life situations and display socially desirable personality traits such as agreeableness and conscientiousness. These social abilities are major contributing factors to mental health (Cohen & Wills, 1985; Holt-Lunstad et al., 2010; Mitchell et al., 1982) and psychological resilience (Nakaya, Oshio, & Kaneko, 2006; Oshio, Taku, Hirano, & Saeed, 2018). While we did not assess the closeness of the momentary social contact in our study, our healthy young participants strongly tended to seek the company of likable people in daily life, as indicated by positive ratings of social contacts in the vast majority of e-diary assessments (~95%). Given this tight relationship between the positive appraisal of social contacts, the detected social affective benefit, and its link to resilience-related social psychological resources, we posit that social affective benefit is a plausible, and likely insufficiently exploited daily-life resilience resource for mental health in the community, and likely also psychiatric patient populations.

Our study has several limitations worth noting. First, we assessed social affective benefit in healthy young adults that rated the social contact in their naturalistic environment as mostly positive (~95% positive contacts). While we confirmed that the social affective benefit effect remained stable when just considering positively rated social contacts, the limited number of prompts with negatively rated social contacts did not allow us to assess this potential stressor of daily affect in more detail. Second, future studies are needed to investigate potential qualitative differences in social affective benefit in patients and at-risk populations with pronounced social impairments such as social anxiety or social anhedonia. In this context, it may be important to examine the underlying salient attributes of positive social contact in more detail, for example by quantifying the composition of the group (i.e., number of males/females, presence of significant others) (Kwapil et al., 2009), as well as how close the individuals feel to the social contact (Brown et al., 2007; Kwapil et al., 2009), a plausible modulator of affect in social situations (Brown et al., 2007). Third, longitudinal studies are necessary to test whether social affective benefit and ACC volume are stable

behavioral resilience mechanisms for mental well-being over the lifespan or more dynamically related. For example, animal studies suggest gray matter volumes in the social brain can be influenced by systematically varying the housing group size in young adult macaques (Sallet et al., 2011), implicating that long-lasting changes in the social environment (e.g., in the context of chronic psychiatric disease) may alter brain structure. As our cross-sectional observational study design and the concurrent measurement of affective valence and social contact limit implications related to the directionality of effects, we can only speculate that ACC structural integrity underpins daily-life SAB. Further experiments are needed to disentangle the causal mechanisms underlying the interplay between ACC structural integrity, mood, and social contact.

Taken together, beneficial social influences are major sources of mental health resilience (Hefner & Eisenberg, 2009; Holz et al., 2020; Mitchell et al., 1982; Victor & Yang, 2012). Consistent with this, we provide evidence that the ability to benefit emotionally from social contact is a robust and fundamental resource for mental well-being in daily life that maps to the ability to utilize social support and maps, at the neural system level, to a much-discussed neural convergence site for psychiatric risk and resilience. Given the technological advances in mobile research and intervention technologies, the real-life social affective benefit may thus represent an important and feasible target phenotype for smartphone-based preventative and therapeutic interventions aiming at identifying, back-feeding, and utilizing daily life social encounters to reduce the mental health risk and mitigate debilitating social symptoms in vulnerable populations and psychiatric patients.

2.6 Supplemental content

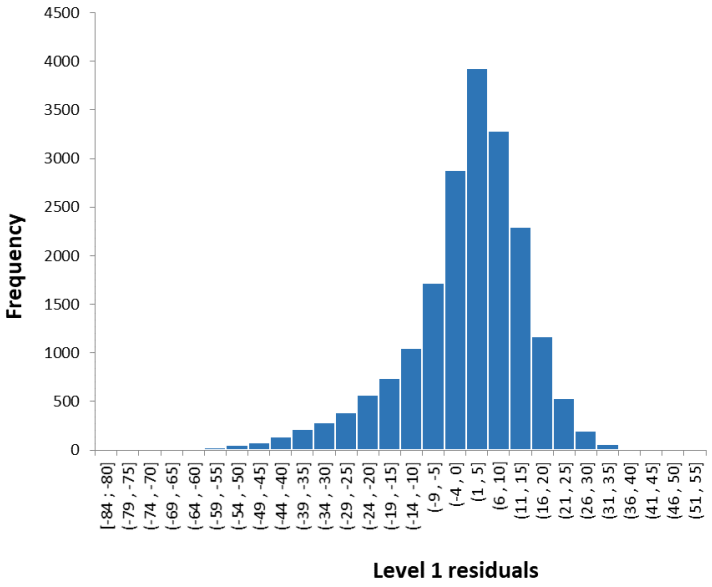

Figure S2.1: Distribution of level-1 residuals of the main hypothesis-testing multilevel model (see Table 2 in the main manuscript). The histogram depicts the distribution (y-axis shows the frequency) of level-1 (assessment-level) residuals (x-axis), which measure deviations from the conditional mean (conditional residuals) derived from our multilevel model (see Methods, section "Data analysis – ambulatory assessment") in the combined sample (discovery and replication study; n = 277 participants). Graphical inspection confirmed that there was no serious deviation from normal distribution providing evidence that our multilevel model is well suited for the given data structure in this large sample.

Table S2.1: Statistical details of the confirmatory multilevel models probing the influence of potential confounders

	Discovery sample					Replication sample				
	n	**B (social contact)**	**SE**	***t* (df)**	***P***	**n**	**B (social contact)**	**SE**	***t* (df)**	***p***
1. Main model + physical activity	89	2.772	0.567	4.89 (75)	**<0.001**	157	2.716	0.409	6.64 (144)	**<0.001**
2. Main model + neuroticism	97	2.575	0.596	4.32 (87)	**<0.001**	160	2.799	0.420	6.67 (147)	**<0.001**
3. Main model + situational context	97	2.746	0.599	4.59 (89)	**<0.001**	162	3.356	0.420	7.99 (155)	**<0.001**
4. Main model + physical activity, situational context	89	2.972	0.572	5.20 (77)	**<0.001**	157	3.329	0.404	8.25 (147)	**<0.001**

5.	Main model + physical activity, neuroticism	89	2.785	0.569	4.90 (75)	**<0.001**	155	2.829	0.402	7.04 (139)	**<0.001**
6.	Main model + neuroticism, situational context	97	2.755	0.600	4.59 (89)	**<0.001**	160	3.458	0.414	8.36 (151)	**<0.001**
7.	Main model + physical activity, neuroticism, situational context	89	2.986	0.574	5.21 (77)	**<0.001**	155	3.444	0.395	8.72 (141)	**<0.001**
8.	Main model - positive contacts only	100	3.432	0.558	6.15 (94)	**<0.001**	177	2.994	0.423	7.07 (171)	**<0.001**

Note: We probed the influence of potential level-1 covariates such as physical activity and situational context as well as level-2 covariates such as neuroticism on the association of social contact and affective valence by computing additional multilevel models based on the main hypothesis-testing model (Table 2, main manuscript) with different covariate combinations. Given that affective valence might be influenced by the quality of social contact, we further tested the social affective benefit effect for prompts with positively rated social contacts only (model 8). In summary, the social affective benefit effect remained highly significant across all tested models. *Abbreviations*: B, beta coefficient; SE, standard error; df, degree of freedom.

Second-order PCA on brief-cope subscales

As suggested by Carver et al. (1989) for the brief-COPE, we performed a second-order oblique PCA on 12 primary brief-COPE subscales to derive a factor structure for our sample by including all subscales except for the alcohol/drugs and religion subscales as these measures were highly skewed and showed low variability in our healthy sample. To determine the factor structure of the brief cope for our sample, we included all participants with brief-cope data from the discovery and replication samples (n = 268; the factor structure was the same when using the replication sample only). This second-order PCA resulted in 4 factors with an eigenvalue greater than 1: active coping (including “planning” and “active coping”), social support (including “emotional” and “instrumental support”, as well as “venting of emotions”), positive coping (including “humor”, “positive reframing”, and “acceptance”), and negation (including “denial”, “self-blame”, “behavioral disengagement”, and “self-distraction”, see **Table S2.2** for details). Following the Scree test, we extracted the four factors that explained 60.1% of the variance in the data. The Kaiser-Meyer-Olkin measure of sampling adequacy was 0.69. Bartlett’s test of sphericity was significant ($\chi^2(66) = 624.57$, $p < 0.001$), indicating that the brief-cope subscales included in the PCA differed sufficiently from

each other. The 4-factor structure was comparable to the second-order PCA performed for the full COPE scale previously (Carver, 1997).

Table S2.2: Brief-cope subscales included in second-order PCA, factor loadings, and communalities

Measures	Factor 1: Social Support	Factor 2: Positive	Factor 3: Negation	Factor 4; Active	Communalities
Using instrumental support	**0.893**	-0.036	-0.028	0.017	0.795
Using emotional support	**0.802**	-0.018	0.093	0.055	0.690
Venting of emotions	**0.789**	-0.043	0.019	-0.084	0.585
Humor	-0.032	**0.798**	-0.100	-0.047	0.605
Positive reframing	0.109	**0.712**	-0.186	0.259	0.670
Acceptance	-0.154	**0.568**	0.168	0.070	0.388
Denial	0.051	-0.179	**0.774**	0.000	0.590
Self-blame	-0.106	-0.119	**0.655**	0.390	0.530
Behavioral disengagement	-0.061	0.312	**0.531**	-0.405	0.568
Self-distraction	0.266	0.197	**0.517**	0.018	0.458
Planning	-0.050	0.040	0.151	**0.825**	0.693
Active coping	0.036	0.131	-0.019	**0.755**	0.638

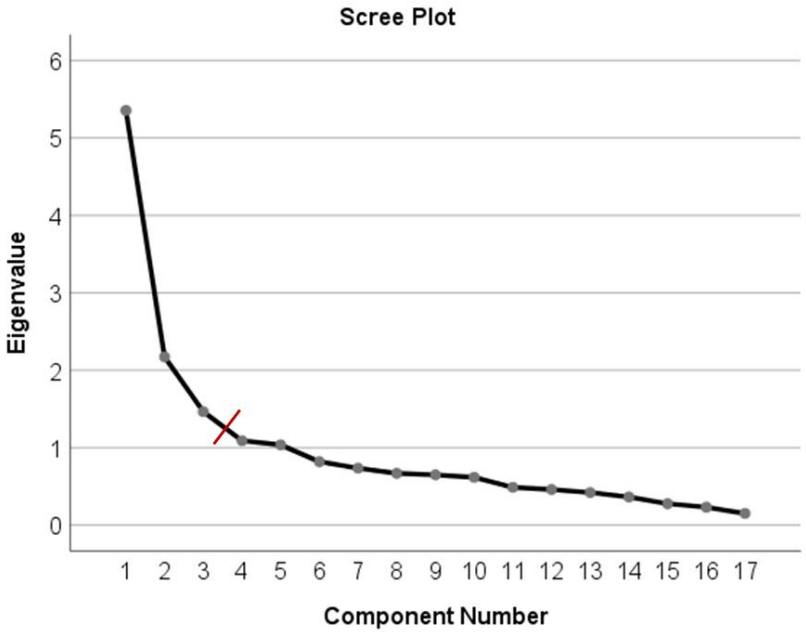

Figure S2.2: Scree-plot showing eigenvalues for the 17 social-psychological measures included in the PCA on social-psychological measures.

We did not consider the SPQ sum score in the PCA because this measure was missing in 30 participants and was highly skewed in our healthy sample. However, a PCA including the SPQ sum score resulted in a comparable factor solution with the SPQ sum score loading primarily on the psychiatric risk factor (factor 1). Only the cope-negation measure loaded primarily on the psychiatric risk (factor 1) instead of the coping factor (factor 3). The correlation between social affective benefit and the social competence factor remained significant (n = 140, Spearman's $r = 0.269$, $p = 0.001$).

3 STUDY 2: LONGITUDINAL ASSOCIATION BETWEEN NEURAL AND REAL-LIFE REWARD PROCESSING AND THE INFLUENCE OF SOCIAL ENVIRONMENTAL RISK FOR PSYCHIATRIC DISORDERS

3.1 Introduction

Neuroimaging studies demonstrate alterations of brain activation in the ventral striatum (VS) during the anticipation of reward across various psychiatric disorders including mood and schizophrenia spectrum disorders (Keren et al., 2018; Schwarz et al., 2020), as well as associations with dimensional measures including anhedonia and depressed mood (Arrondo et al., 2015; Schwarz et al., 2020). These studies suggest that altered VS reactivity may constitute a transdiagnostic intermediate neural phenotype of risk for psychiatric disorders. On the other hand, ambulatory assessment studies demonstrate that affective reactivity to positive events, a real-life measure of reward-related experiences conceptualized as the degree to which participant's momentary positive affect increased in response to daily-life positive events intensity, was specifically pronounced in psychiatric patients with major depression and adolescents and young adults reporting low well-being (Grosse Rueschkamp et al., 2020; Peeters et al., 2003). While affective reactivity to positive events might be an important protective daily-life reward-related resource mitigating low well-being in healthy and at-risk populations, its neural basis is unknown.

Thus, in an accelerated longitudinal design with three measurement time points, we combined smartphone-based ambulatory assessment of daily-life affective reactivity to positive events with functional magnetic resonance imaging (fMRI) measuring VS reactivity during the anticipation of monetary rewards using a well-established monetary incentive delay task (MID) (Schwarz et al., 2020) in 105 healthy participants aged 12 to 28 years. We first examined in neuroimaging space at baseline whether daily-life affective reactivity to positive events was related to VS reactivity during reward anticipation at the between-subject level. Second, we used multilevel modeling to test whether VS reactivity (extracted from an unbiased VS mask) and affective reactivity to positive events co-evolve across three annually separated time points while controlling for the developmental effect on VS reactivity described previously (Braams et al., 2015). We expected a positive between- and within-subject relationship between VS reactivity and affective reactivity to positive events given previous cross-sectional neuroimaging-

ambulatory assessment studies suggesting positive associations between striatal responses during reward anticipation and other real-life reward-related measures (e.g., anticipation/momentary enjoyment of pleasant events) (Forbes et al., 2009; Moran et al., 2019). Moreover, we explored whether participants' psychological and social environmental risk for psychiatric disorders determined by a principal component analysis (PCA) of standard inventory measures moderated the observed within-subject relationship between reward-related VS reactivity and affective reactivity to positive events.

3.2 Results and Discussion

For all following analyses, we used individual daily-life affective reactivity to positive events as our main predictor computed by separate random-intercept random-slope multilevel model for baseline, the second time point (T2), and the third time point (T3) with momentary positive events intensity as the predictor of interest, and momentary positive affect as the outcome measure, as well as time of day, time of day squared (level-1), age, and sex (level-2) as covariates. Multilevel models for all three time points revealed highly significant within-subject associations between positive events intensity and positive affect (see **Table S3.2**); consistent with previous research (Grosse Rueschkamp et al., 2020), participants experienced higher positive affect when they rated positive events as more intense.

3.2.1 Between-subject association between VS reactivity and affective reactivity to positive events at baseline

To assess whether individual affective reactivity to positive events (predictor of interest) and VS reactivity during reward anticipation (outcome measure; contrast of interest: "win > neutral"; see supplementary content for details) were associated at the between-subject level at baseline, we used SPM12 to compute voxel-wise univariate regression analyses within the VS (our region of interest, ROI), while controlling for age and sex. This analysis revealed a significant positive association between daily-life affective reactivity to positive events and VS reactivity (peak voxel: x=-9, y=14, z=-1; t = 2.9, p_{FWE} = 0.047, peak-level family-wise error (FWE), ROI-corrected, **Figure 3.1**). No other brain area showed significant associations with affective reactivity to positive events across the whole brain. Thus, individuals with a larger increase in positive affect related to positive events in daily life showed higher VS reactivity when

anticipating a monetary win. This finding suggests that a widely studied intermediate neural phenotype of psychiatric disorders is linked to emotional benefit from positive events, a potential daily-life resource for mitigating low mood in patients with major depression, as well as in healthy adolescents and young adults (Grosse Rueschkamp et al., 2020; Peeters et al., 2003). Together with previous cross-sectional studies using various neural and daily-life reward-related measures (Forbes et al., 2009; Moran et al., 2019), our results corroborate that neural reward responses are linked to daily-life reward experiences, here for two widely used phenotypes that have previously been linked to psychopathology.

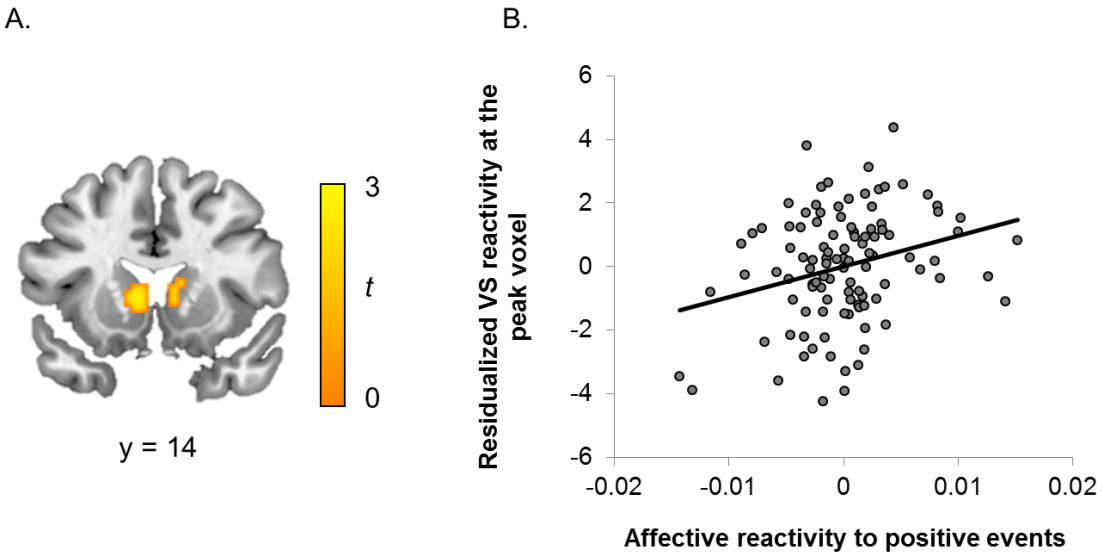

Figure 3.1. Association between affective reactivity to positive events and VS reactivity at baseline. A. Brain map showing the positive association between affective reactivity to positive events and VS reactivity during reward anticipation at baseline. Affective reactivity to positive events was conceptualized as the degree to which each participant's momentary positive affect was related to the intensity of daily-life positive events (i.e., the random effects based on the multilevel model). For display purposes, the brain map was displayed at a threshold of $p < 0.005$ uncorrected across the whole brain. **B.** Scatterplot showing the positive between-subject association between affective reactivity to positive events (x-axis) and VS reactivity (y-axis) at baseline. VS, ventral striatum.

3.2.2 Within-subject association between VS reactivity and affective reactivity to positive events across three measurement time points

To further assess within-subject associations in our longitudinal accelerated design with three annually separated time points, VS reactivity was extracted from first-level contrast images (mean "win > neutral" contrast estimates across an unbiased VS mask

(Moessnang et al., 2016), see supplementary content) computed for each time point separately. Random-intercept multilevel model analyses with the extracted VS reactivity as the outcome variable and individual affective reactivity to positive events as the predictor (level-1), as well as age (level-1, here representing the three time points for each individual) and sex (level-2) as covariates of no interest, revealed a significant within-subject association between VS reactivity and affective reactivity to positive events (β = 43.866, p = 0.047, **Table 1A**). Importantly, supplemental analyses revealed that the within-subject association between VS reactivity and affective reactivity to positive events based on the main multilevel model (**Table 1A**) was neither moderated by age nor age-squared (see **Table S3.4B/C**) suggesting that the within-subject association was independent of a previously reported developmental effect on striatal functioning that we could replicate in our adolescent/young adult cohort (**Figure S3.3**, **Table S3.4A**). Our findings extend previous cross-sectional work (Forbes et al., 2009; Moran et al., 2019) by showing that affective reactivity to positive events and VS reactivity are tightly coupled within subjects across three measurement time points in a longitudinal study design. Thus, increased affective reactivity to positive events at any time point was associated with increased VS reactivity at any time point, independent of the chronological order of time points (or age), suggesting that real-life and laboratory-based neural reward measures co-evolve over time.

Table 1. Multilevel models of the within-subject association between VS reactivity and affective reactivity to positive events (A), and the moderation effect of social environmental risk (B).

A. *Model 1: VS reactivity = affective reactivity to positive events + age + sex (n = 100)*				
Fixed effects				
Predictor	B	SE	*t* (df)	*p*
Intercept	2.1211	0.6911	3.07 (132)	**0.0026**
Affective reactivity to positive events	43.8661	21.9756	2.00 (199)	**0.0473**
Age (years)	0.02482	0.03158	0.79 (135)	0.4332
Sex: female	0.2233	0.2882	0.77 (98)	0.4403
Random effects				
Predictor	Variance estimate	SE	Wald-*Z*	*p*
Intercept	1.4360	0.3008	4.77	**<0.0001**
B. *Model 2: VS reactivity = affective reactivity to positive events + social environmental risk + affective reactivity to positive events*social environmental risk + age + sex (n = 85)*				
Fixed effects				
Predictor	B	SE	*t* (df)	*p*
Intercept	1.8654	0.7613	2.45 (115)	**0.0158**
Affective reactivity to positive events	40.4666	21.8157	1.85 (168)	0.0654
Social environmental risk	-0.04619	0.1607	-0.29 (81)	0.7745
Affective reactivity to positive events * social environmental risk	48.0802	23.7561	2.02 (168)	**0.0446**
Age (years)	0.03795	0.03498	1.08 (119)	0.2802
Sex: female	0.1802	0.3201	0.56 (81)	0.5750
Random effects				
Predictor	Variance estimate	SE	Wald-*Z*	*p*
Intercept	1.5629	0.3373	4.63	**<0.0001**

Note: B, beta coefficient; SE, standard error; df, degree of freedom. See supplementary content for full equation of the multilevel model. Random slopes for level-1 predictors were not added because of only three time points which is too few to estimate random slopes.

3.2.3 Moderation of the within-subject association between VS reactivity and affective reactivity to positive events by social environmental risk

We further explored whether the within-subject association between VS reactivity and affective reactivity to positive events was moderated by *psychological risk*, *low social status*, or *social environmental risk,* three higher-order factors determined by a PCA of standard inventory measures assessed at baseline (see **Table S3.5**). For each PCA factor, separate multilevel model analyses testing for an interaction between affective reactivity to positive events and the PCA factor on VS reactivity (covariates: age, sex)

revealed that only the *social environmental risk* factor significantly moderated the within-subject association between VS reactivity and affective reactivity to positive events (see **Fig. 3.2** and **Table 1B)**. Thus, individuals with high social environmental risk indicated by higher urban upbringing scores and a smaller social network size demonstrated a positive association between VS reactivity and affective reactivity to positive events within subjects across 3 years. In contrast, no within-subject association was observed in individuals with low social environmental risk. Our data suggest that VS reactivity and affective reactivity to positive events co-evolve over time specifically in individuals with previously discussed social environmental risk factors for psychiatric disorders such as urban upbringing and limited social resources (Meyer-Lindenberg & Tost, 2012; Selten, van der Ven, Rutten, & Cantor-Graae, 2013). Thus, given previous work in patients with major depression and low mood in healthy individuals (Grosse Rueschkamp et al., 2020; Peeters et al., 2003), we speculate that for at-risk individuals from our healthy sample, the ability to enjoy positive experiences in daily life may be an important daily-life resource to compensate for reduced VS reactivity, an intermediate phenotype for psychiatric disorders (Keren et al., 2018; Schwarz et al., 2020). Post-hoc correlation analyses with social environmental risk (continuous measure) indeed showed that at baseline, individuals with higher social environmental risk demonstrate higher affective reactivity to positive events (Pearson's r = 0.230, p = 0.029; **Figure 3.3**), but do not differ from individuals at lower social environmental risk in VS reactivity (Pearson's r = -0.154, p = 0.145).

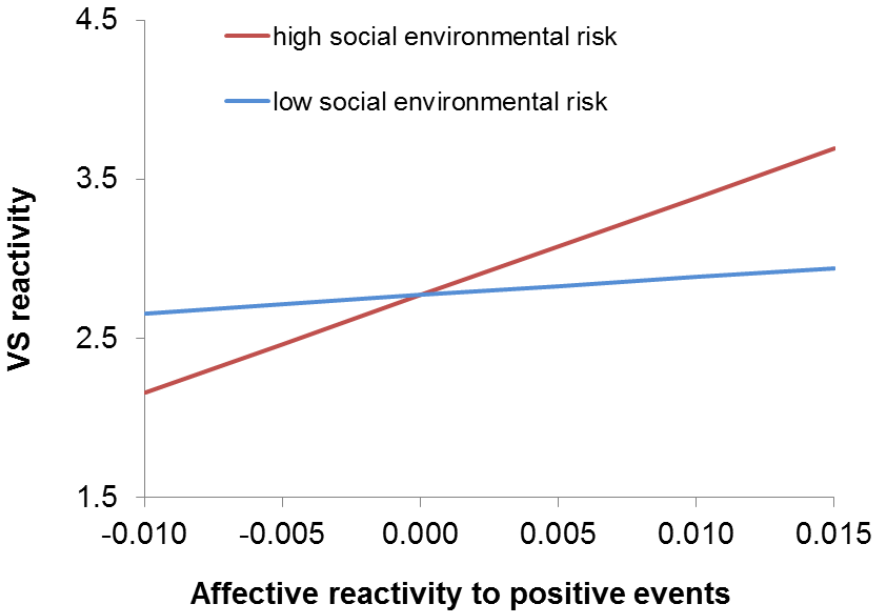

Figure 3.2. The moderation of within-subject association between affective reactivity to positive events and VS reactivity across three measurement time points by social environmental risk. Social environmental risk moderates the within-subject association between affective reactivity to positive events (x-axis) and VS reactivity (y-axis). For display purposes, the social environmental risk (continues variable) was dichotomized into low social environmental risk (33rd quantile) and high social environmental risk (67th quantile). This association was independent of the chronological order of the time points (predictor: age). VS, ventral striatum.

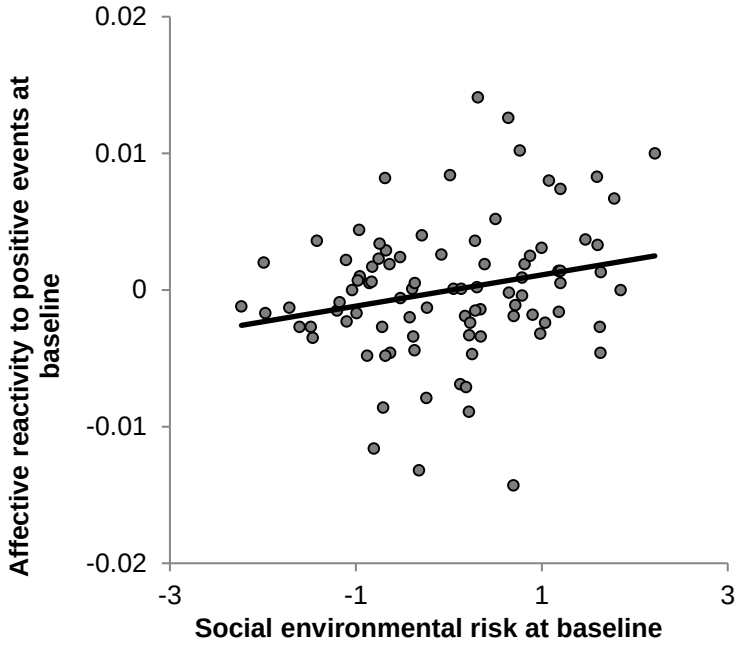

Figure 3.3. Individuals with high social environmental risk tend to show increased affective reactivity to positive events at baseline.

Our observational study design limits any causal implications of the association between VS reactivity and affective reactivity to positive events. While we cannot establish a directionality of effects, we speculate based on the existing literature on the causal influence of environmental exposures (e.g., urban green space, nature experience) on neural activity (Bratman et al., 2015; Tost et al., 2019), that a change in VS reactivity across longitudinal measurements could be driven by a change in affective reactivity to positive events in real life. If this is true, affective reactivity to positive events could be an important target for mobile health interventions aiming at improving low daily mood in psychiatric patients and the general population. However, further experimental studies with more longitudinal measurement waves are needed to better understand whether experimentally manipulating affective reactivity to positive events could affect VS reactivity in the long run and improve psychiatric conditions.

In conclusion, our study corroborates that laboratory-based striatal reward processing is linked to real-life reward-related experiences at the between- as well as the within-subject level, an effect specifically pronounced in individuals with high social environmental risk. Our findings thus open up the possibility of an evidence-based policy for mobile mental health interventions.

3.3 Materials and Methods

A detailed materials and methods section can be found in the supplementary content. All participants (see **Table S3.1** for sample characteristics) completed a 7-day smartphone-based ambulatory assessment, a battery of standard social and psychological online inventories, and the MID task during fMRI. Participants completed this assessment protocol within an accelerated longitudinal design at three annually separated assessment time points. All participants provided written informed consent for a study protocol approved by the institutional review board of Heidelberg University. Raw data and analysis codes are available from the corresponding authors upon reasonable request.

3.4 Supplementary content

3.4.1 Participants

Healthy participants were recruited from local communities in the framework of psychoepidemiological center (PEZ) at Central Institute of Mental Health (CIMH) in Mannheim, Germany (Tost et al., 2019). In PEZ, participants from an age of 12 to 28 years were recruited at baseline and then followed up on annually up to three waves, according to an accelerated longitudinal design. In each assessment wave, participants completed a standard battery of self-report questionnaires regarding sociodemographic and subclinical information, and were enrolled in an MRI scanning session and in a one-week GPS-triggered, smartphone-based ambulatory assessment. Data were collected from September 1, 2014 to July 31, 2019. 122 participants completed all three measurement waves.

Exclusion criteria included a lifetime history of general medical, psychiatric, or neurological illness; psychopharmacological or psychotherapeutical treatment; drug or alcohol abuse; head trauma; and standard MRI exclusion criteria (e.g., metal implants, claustrophobia). In the baseline (T1) between-subject analyses, 105 participants were included (excluded n = 16; reasons for exclusion: n = 12, excessive head motion during fMRI scanning; n = 3, potential psychological problems; n = 1, potential multiple sclerosis; n = 1, ambulatory assessment compliance < 30%). Demographic and psychological characteristics of these 105 participants are displayed in Table S3.1. In the within-subject analyses, another five participants were excluded because of missing ambulatory assessment data (n = 4) or low ambulatory assessment compliance (n = 1) at T2 or T3. All participants provided informed consent before study participation and received monetary compensation.

Table S3.1: Demographic and psychological characteristics

	Mean	Standard deviation	n
Demographic data			
Age (years)	19.64	4.22	105
Sex (females/males)	50/55		105
Education (years)	11.40	2.38	103
Psychological and social environmental measures			
Trait anxiety (STAI-T, sum)	33.43	7.24	103
Neuroticism (NEO-FFI-30-N, mean)	25.95	7.11	105
Sense of coherence (SOC, sum)	147.33	21.92	102

Chronic stress (SSCS, sum)	14.79	8.07	105
Well-being (WHO-5, %)	63.80	16.57	100
Life satisfaction (SWLS, sum)	27.57	4.77	101
Self-efficacy (SWE, sum)	30.44	3.66	101
Socioeconomic status (SES, aggregate score)	15.13	3.38	105
Early life family social status	6.19	1.41	102
Urban upbringing	32.45	9.99	104
Social network size (SNI)	20.01	8.74	104

3.4.2 Ambulatory assessment data acquisition and analysis

Participants completed a 7-day smartphone-based ambulatory assessment in daily life. They responded to 9-23 possible e-diary assessments every day between 7:30 and 22:30. For the implementation of the e-diaries and sampling strategy, we used the ambulatory assessment software movisensXS, version 0.6.3658 (movisens GmbH, Germany, https://xs.movisens.com). Details on the sampling schedule can be found in ref. (Tost et al., 2019).

In adults, momentary positive affect were assessed with items adapted from previous studies (Geschwind et al., 2010; Wilhelm & Schoebi, 2007). Positive affect items were *cheerful, content, energetic, enthusiastic, relaxed, and happy*, rated on 1-7 Likert scales. Also, participants reported whether they had experienced any positive events since the last prompt and rated the intensity of the positive events on visual analogue scales from 0 (no event) to 100 (very intense). In case of multiple events, participants were asked to rate the most intense event. In adolescents, we used the 10 items from ref. (Leonhardt, Könen, Dirk, & Schmiedek, 2016) to assess momentary affect. These items were showed to be sensitive to affect fluctuations and comprehensible to children (Leonhardt et al., 2016). Positive affect items include *active, cheerful, concentrated, content, delighted, fantastic, good, interested, pleasant, and rested*. These 10 items were also rated on 1-7 Likert scales. Adolescents rated positive events on 8-point Likert scales from 0 (no event) to 7 (very intense). In the analyses, adolescents' event appraisals were rescaled to 0-100 so as to be consistent with the adults'. Positive affect was computed as the mean of positive items for each prompt.

Figure S3.1. Illustration of positive affect items (left panel) and positive events intensity item (right panel) during ambulatory assessment.

To calculate the real-life affective reactivity to positive events for each measurement time point, positive affect was regressed on positive events intensity (subject-mean centered) at each e-diary assessment with SAS (version 9.4., SAS Institute Inc., Cary, NC, USA), resulting in a two-level multilevel model with level-1 measures from each e-diary assessment nested within participant at level-2. In this model, we also added the level-1 predictors time and time-squared to control for the effects of time of day on positive affect, and included sex and age as level-2 covariates of no interest. To capture the individual difference in real-life affective reactivity to positive events, random effects of positive events intensity were also incorporated in the model. The equation representation was as follows:

Equation S3.1:

$$
\begin{aligned}
&Y(\boldsymbol{positive\ affect})_{ij} \\
&\quad = \beta_{00} + \beta_{01} * age_j + \beta_{02} * sex_j + \boldsymbol{\beta_{10}} * \boldsymbol{positive\ event\ intensity_{ij}} \\
&\quad + \beta_{20} * time\ of\ day_{ij} + \beta_{30} * time\ of\ day_{ij}^2 + u_{0j} + \boldsymbol{u_{1j}} \\
&\quad * \boldsymbol{positive\ event\ intensity_{ij}} + u_{2j} * time\ of\ day_{ij} + r_{ij}
\end{aligned}
$$

Here Y_{ij} represents the positive affect at the *i*'th e-diary assessment for the *j*'th participant. Real-life affective reactivity to positive events was computed as the individual slopes of positive events intensity, i.e., the random effects of positive events intensity ($\boldsymbol{u_{1j}}$). Thus, each participant had three measures of real-life affective reactivity to positive events for each of the three measurement time points. The multilevel models

for T1, T2, and T3 were displayed in **Table S3.2**, which indicated that increased positive affect was associated with higher positive events intensity at all three time points. Affective reactivity to positive events was calculated as the individual slope values from the random effect of positive events intensity on positive affect (i.e., the person-specific deviation from the fixed group effect) in the multilevel model, which reflect the individual differences in the strength of association between the positive affect and positive events intensity. Given that our sample consisted of both adolescents and adults, we also conducted the previous multilevel models in adolescents and adults separately as shown in **Table S3.3**. The results suggested that the positive affect was significantly associated with positive events intensity in both the adolescent and adult cohorts.

Table S3.2. Multilevel modeling of affective reactivity to positive events at T1, T2 and T3.

	T1 (n = 105)			**T2** (n = 100)			**T3** (n = 100)		
Fixed effects									
Predictor	B (SE)	*t* (df)	*p*	B (SE)	*t* (df)	*p*	B (SE)	*t* (df)	*p*
Intercept	5.1090 (0.4328)	11.80 (99)	**<0.0001**	4.9267 (0.4567)	10.79 (102)	**<0.0001**	4.2014 (0.4852)	8.66 (104)	**<0.0001**
Level-1 predictors									
positive events intensity	0.0088 (0.0008)	11.03 (72)	**<0.0001**	0.0096 (0.0008)	11.69 (87)	**<0.0001**	0.0111 (0.0009)	12.19 (73)	**<0.0001**
Time (hours)	0.1045 (0.0109)	9.59 (1430)	**<0.0001**	0.1023 (0.0106)	9.63 (2442)	**<0.0001**	0.1189 (0.0103)	11.56 (1040)	**<0.0001**
Time-squared ($hours^2$)	-0.0058 (0.0006)	-9.08 (5533)	**<0.0001**	-0.0058 (0.0006)	-9.09 (5767)	**<0.0001**	-0.0064 (0.0006)	-11.11 (5926)	**<0.0001**
Level-2 predictors									
Age (years)	-0.0379 (0.0202)	-1.87 (95)	0.0643	-0.0374 (0.0208)	-1.80 (98)	0.0753	0.0050 (0.0210)	-0.24 (100)	0.8111
Sex: female	-0.3184 (0.1747)	-1.82 (93)	0.0716	-0.0356 (0.1717)	-0.21 (96)	0.8361	0.0441 (0.1814)	0.24 (98)	0.8083
Random effects									
Predictor	Variance estimate (SE)	Wald-*Z*	*p*	Variance estimate (SE)	Wald-*Z*	*p*	Variance estimate (SE)	Wald-*Z*	*p*
Intercept	0.7238 (0.1139)	6.36	**<0.0001**	0.6828 (0.1039)	6.57	**<0.0001**	0.7628 (0.1160)	6.58	**<0.0001**
positive events intensity	0.00004 (9.95E-6)	4.13	**<0.0001**	0.00004 (8.82E-6)	4.46	**<0.0001**	0.00006 (0.00001)	4.49	**<0.0001**
Time (hours)	0.0016 (0.0004)	4.10	**<0.0001**	0.0007 (0.0002)	3.35	**0.0004**	0.0021 (0.0004)	5.03	**<0.0001**

Note: B, beta coefficient; SE, standard error; df, degree of freedom.

Table S3.3. Multilevel modeling of affective reactivity to positive events in adolescents and adults separately at T1, T2 and T3.

	T1			**T2**			**T3**		
Predictor	B (SE)	*t* (df)	*p*	B (SE)	*t* (df)	*p*	B (SE)	*t* (df)	*p*
Adolescents									
positive events intensity	0.0071 (0.0013)	5.47 (36)	**<0.0001**	0.0072 (0.0012)	5.81 (31)	**<0.0001**	0.0085 (0.0014)	6.10 (25)	**<0.0001**
Adults									
positive events intensity	0.0100 (0.0010)	9.86 (39)	**<0.0001**	0.0110 (0.0010)	10.63 (58)	**<0.0001**	0.0122 (0.0011)	10.72 (49)	**<0.0001**

Note: B, beta coefficient; SE, standard error; df, degree of freedom.

3.4.3 fMRI data acquisition, preprocessing, and first-level analysis

We used an adapted version of a well-established monetary incentive delay paradigm (Grimm et al., 2014) in which subjects were asked to give speeded responses (button press) to a visual target (**Figure S3.2**). Trials were grouped into two experimental conditions based on the cues preceding the visual target: If the cue was an arrow pointing upwards, the trial was a win trial (win condition) and subjects had the chance to win 2€. The feedback stimulus was presented as a 2€ coin if their response time was under threshold, or a blurred coin picture if their responses were not fast enough. If the cue was a double-sided horizontal arrow, the trial was a neutral trial (neutral condition). In this case, subjects would not get a reward no matter how they responded to the target. A total of 15 trials per condition were presented in a pseudorandomized order over the course of the experiment. The threshold for a fast response was adaptive for each trial to ensure that subjects were able to win some money and work on their maximum performance level.

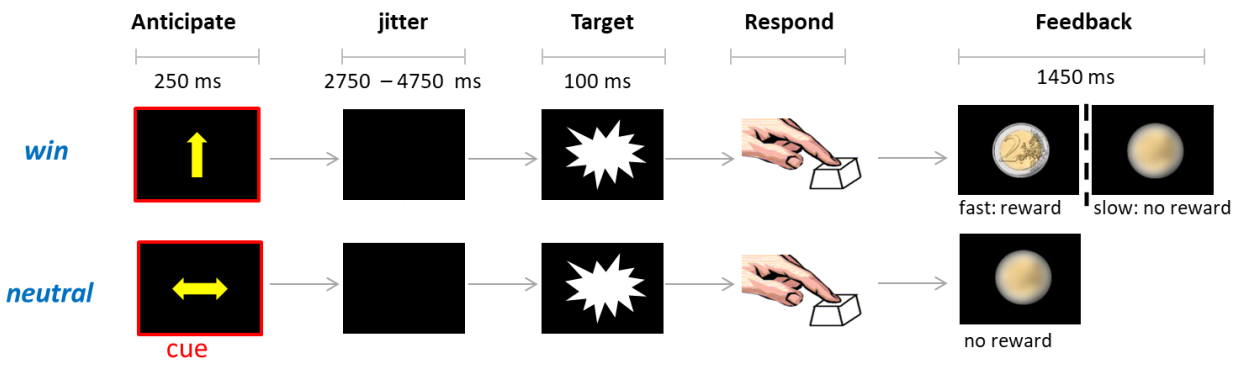

Figure S3.2. Monetary incentive delay task. Subjects were asked to give speeded responses to a visual target (brief light flash). Preceding cues indicated whether subjects have the chance to win 2 Euros (win condition) if the response is fast enough or they will not get monetary reward despite their responses (neutral condition).

Functional MRI (fMRI) data were acquired at CIMH on a 3 Tesla MRI scanner (Siemens Trio, Erlangen, Germany) with an echo-planar imaging (EPI) sequence (TE: 30 ms, TR: 2 s, flip angle: 80°, matrix: 64 × 64, FOV: 192 × 192 mm, in-plane resolution: 3 x 3 mm, slice thickness: 4 mm, 28 axial slices, 151 volumes). Image preprocessing followed standard preprocessing routines in SPM12 (http://www.fil.ion.ucl.ac.uk/spm), including slice time correction, realignment to the mean image, spatial normalization based on the Montreal Neurological Institute (MNI) template, resampling, and smoothing. Framewise displacement (FD) was computed as the head motion parameter used for fMRI quality control (Power, Barnes, Snyder, Schlaggar, & Petersen, 2012). Using same exclusion criterion for head motion as in our previous study on brain activation during reward processing (Schwarz et al., 2020), any participant with mean framewise displacement > 0.5 mm or more than 20% volumes with framewise displacement > 0.5mm in any of the three measurement time points was excluded from the remaining analyses.

For first-level analysis, task events were modeled as stick functions and resulting regressors pertaining to win cues, control cues, visual targets and feedbacks were entered as into a general linear model. Six head motion parameters from the realignment step were included as nuisance covariates. During model estimation, a high-pass filter with a cutoff of 128 seconds and an autoregressive model of the first order were applied. Brain responses during reward anticipation were defined as differential response between win cues and neutral cues (contrast “win cue > neutral cue”).

3.4.4 Between-subject association between VS reactivity and real-life affective reactivity to positive events

For analysis of the between-subject association between VS reactivity and real-life affective reactivity to positive events, we used a univariate regression model in SPM12 with individual affective reactivity to positive events as the regressor of interest (see point 2 “Ambulatory assessment data acquisition and analysis”), and age and sex as covariates. Significance was measured at $p < 0.05$ voxel-wise family-wise error (FWE) corrected within an a priori defined mask of the ventral striatum (VS), the core area of the neural reward system. The VS mask consists of the “caudate head” mask from the WFU-PickAtlas (human-atlas TD brodmann areas+) and the “accumbens” mask from the Harvard–Oxford Subcortical Structural Atlas (Plichta et al., 2012). To optimize the reliability of functional responses, this mask was refined by a test-retest study performed in an independent sample (n = 28, mean age: 22.9 ± 2.8 years, 14 females, see ref. (Moessnang et al., 2016)) that allows us to retain only those voxels in the mask that show sufficient test-retest reliability, i.e., intraclass correlation coefficient > 0.4. Outside our ROI, we considered findings to be significant if they passed a significance threshold of $p < 0.05$ FWE corrected for multiple comparisons across the whole brain.

3.4.5 Developmental trajectory of VS reactivity

Using a one-sample t-test, we confirmed that anticipating a “win” vs. a “neutral” condition significantly activated the brain’s reward network including the ventral striatum, our region of interest, for all three measurement time points (**Figure S3.3**). Mean VS reactivity (“win > neutral” contrast estimates) within the VS test-retest mask was extracted from each measurement time point for each participant. A repeated-measures ANOVA did not reveal significant within-subject differences across the three time points ($F(2, 190) = 1.118$, $p = 0.327$, Greenhouse-Geisser correction), meaning the measurement time points did not affect VS reactivity during reward anticipation. Using a multilevel model with this mean VS reactivity as the outcome variable, and age and age-squared as level-1 predictors nested within participants across the three measurement time points (see Equation S3.2), we observed significant linear ($\beta = 0.805$, $p = 0.002$) and quadratic age effects ($\beta = -0.019$, $p = 0.003$). Specifically, we confirmed that the predicted mean VS reactivity from the multilevel model follows an inverted-U shaped developmental trajectory across the ages of 12 to 30 years (**Figure S3.4**).

Equation S3.2:

$$Y(\boldsymbol{VS\ reactivity})_{ij} = \beta_{00} + \beta_{10} * age_{ij} + \beta_{20} * age_{ij}^2 + u_{0j} + r_{ij}$$

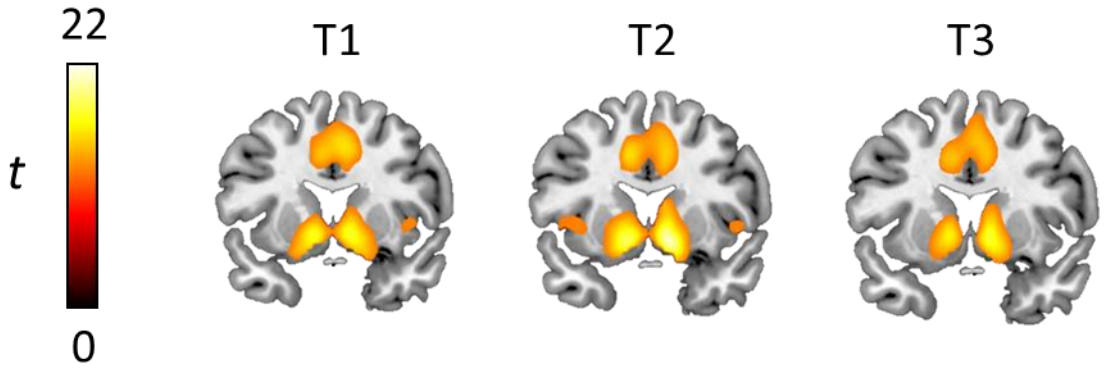

Figure S3.3. Whole-brain activation during reward anticipation (win > neutral) across all participants for each measurement time point. For visualization purposes, activations below t<12 are not displayed.

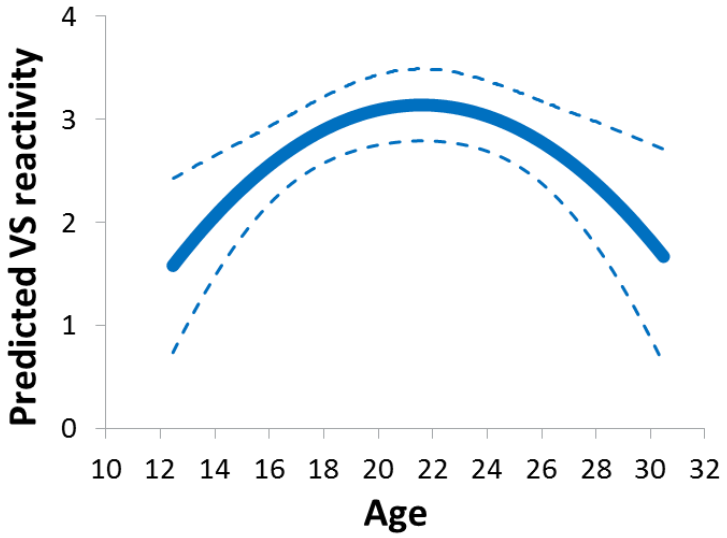

Figure S3.4. Developmental trajectory of VS reactivity as determined by the multilevel model. The bold line depicts the fixed developmental effect across all participants, and the dashed lines represent the 95% confidence interval. VS, ventral striatum.

3.4.6 Within-subject association between VS reactivity and affective reactivity to positive events

To examine the association between VS reactivity and real-life affective reactivity to positive events over the three measurement time points, we built a multilevel model with the extracted mean VS reactivity as the outcome variable and real-life affective reactivity to positive events as the main predictor, while including age and age-squared as covariates of no interest. Real-life affective reactivity to positive events was centered at each participant's mean value across the three measurement time points because we were particularly interested in the fluctuations relative to each participant's own average rather than the between-subject differences across the study period. Equation S3.3 details the full model:

Equation S3.3:

$$Y(\boldsymbol{VS\ reactivity})_{ij} = \beta_{00} + \beta_{10} * age_{ij} + \beta_{20} * age_{ij}^2 + \beta_{30} * sex_j + \boldsymbol{\beta_{40}} * \boldsymbol{affective\ reactivity\ to\ positive\ events_{ij}} + u_{0j} + r_{ij}$$

Here Y_{ij} represents the VS reactivity at the *i*'th measurement time point for the *j*'th participant. β_{00} represents the group intercept, β_{10}, β_{20}, β_{30} represent the group effects of age, age-squared, and sex. β_{40} represents the effect of affective reactivity to positive events. u_{0j} denotes the random effect of the intercept. The residuals are denoted as r_{ij}.

Table S3.4. Tests of striatal developmental effect on the within-subject association between VS reactivity and affective reactivity to positive events

A. *Model S1: VS reactivity = affective reactivity to positive events + age + age-squared + sex (n = 100)*				
Predictor	B	SE	*t* (df)	*p*
Intercept	-4.5118	2.7481	-1.64 (235)	0.1020
Affective reactivity to positive events	44.7290	22.2105	2.01 (195)	**0.0454**
Age (years)	0.6892	0.2692	2.56 (245)	**0.0111**
Age-squared (years^2)	-0.0159	0.0064	-2.48 (251)	**0.0138**
Sex: female	0.1599	0.2764	0.58 (95)	0.5642
B. *Model S2: VS reactivity = affective reactivity to positive events + age + age-squared + affective reactivity to positive events*age + sex (n = 100)*				
Predictor	B	SE	*t* (df)	*p*
Intercept	-4.3960	2.7557	-1.60 (235)	0.1120
Affective reactivity to positive events	118.50	108.77	1.09 (199)	0.2772
Age (years)	0.6772	0.2700	2.51 (245)	**0.0128**
Age-squared (years^2)	-0.0156	0.0064	-2.43 (250)	**0.0159**
Affective reactivity to positive events*age	-3.6906	5.3262	-0.69 (200)	0.4892
Sex: female	0.1618	0.2766	0.59 (95)	0.5599
C. *Model S3: VS reactivity = affective reactivity to positive events + age + age-squared + affective reactivity to positive events*age-squared + sex (n = 100)*				
Predictor	B	SE	*t* (df)	*p*
Intercept	-4.3922	2.7551	-1.59 (235)	0.1122
Affective reactivity to positive events	84.3539	58.2416	1.45 (199)	0.1491
Age (years)	0.6767	0.2699	2.51 (245)	**0.0128**
Age-squared (years^2)	-0.0155	0.0064	-2.43 (250)	**0.0160**
Affective reactivity to positive events*age-squared	-0.0949	0.1289	-0.74 (200)	0.4626
Sex: female	0.1623	0.2766	0.59 (95)	0.5587

Note: B, beta coefficient; SE, standard error; df, degree of freedom. All three models are random-intercept models, so only results of fixed effects are displayed.

3.4.7 Characterization of psychological and social environmental measures

At baseline measurement, participants completed an online questionnaire battery including basic socio-demographic measures from which we computed socioeconomic status (SES) (Lampert et al., 2013), and psychological and social environmental measures indicating trait anxiety (STAI-T) (Laux et al., 1981), trait neuroticism (NEO-FFI) (Borkenau & Ostendorf, 2008), sense of coherence (SOC) (Hannöver et al., 2004), chronic stress (SSCS) (Schulz, Schlotz, & Becker, 2004), well-being (WHO-5) (Krieger et al., 2014), satisfaction with life (SWLS) (Glaesmer et al., 2011), self-efficacy (SWE)

(Jerusalem & Schwarzer, 1992), early life family social status (Adler, Epel, Castellazzo, & Ickovics, 2000; Goodman et al., 2001; Hoebel, Müters, Kuntz, Lange, & Lampert, 2015), urban upbringing (Mortensen et al., 1999) and social network size (SNI) (Cohen et al., 1997).

To identify high order dimensions of the psychological and social environmental measures, we performed a principal component analysis (PCA) with SPSS 22.0 (IBM) in 91 participants with complete data for 11 measures (see **Table S3.1**). The PCA resulted in three factors mapped onto dimensions of psychological risk, social status, and social environmental risk with an eigenvalue greater than 1 (see **Figure S3.4**). The three factors explained 61.8% of the variance in the data. The Kaiser-Meyer-Olkin measure of sampling adequacy was 0.791, and thus above the recommended minimum of 0.6 for exploratory PCAs. The Bartlett's test of sphericity was significant ($\chi^2(55) = 381.947$, $p < 0.001$), indicating that the measures included in the PCA differed sufficiently from each other. Finally, we applied a varimax rotation in order to reach orthogonality between the factors and thereby simplify interpretation of the factors (for communalities and factor loadings of all included measures, see **Table S3.5**).

Table S3.5: PCA on psychological and social environmental measures.

Measures	Abbr.	Factor 1: Psychological risk	Factor 2: Low social status	Factor 3: Social environmental risk	Communalities
Trait anxiety (sum score)	STAI-T	0.910			0.839
Neuroticism (mean score)	NEO-N	0.846			0.721
Sense of coherence (sum score)	SOC	-0.819			0.699
Chronic Stress (sum score)	SSCS	0.779			0.682
Well-being (percent)	WHO-5	-0.619			0.452
Satisfaction with life (sum score)	SWLS	-0.614			0.623
Self-efficacy (sum score)	SWE	-0.542			0.480
Socioeconomic status	SES		-0.808		0.658
Early life family social status			-0.788		0.647
Urban upbringing				0.727	0.551
Social network size	SNI			-0.600	0.448

Note: only factor loadings > .5 were displayed. Abbr.: Abbreviation

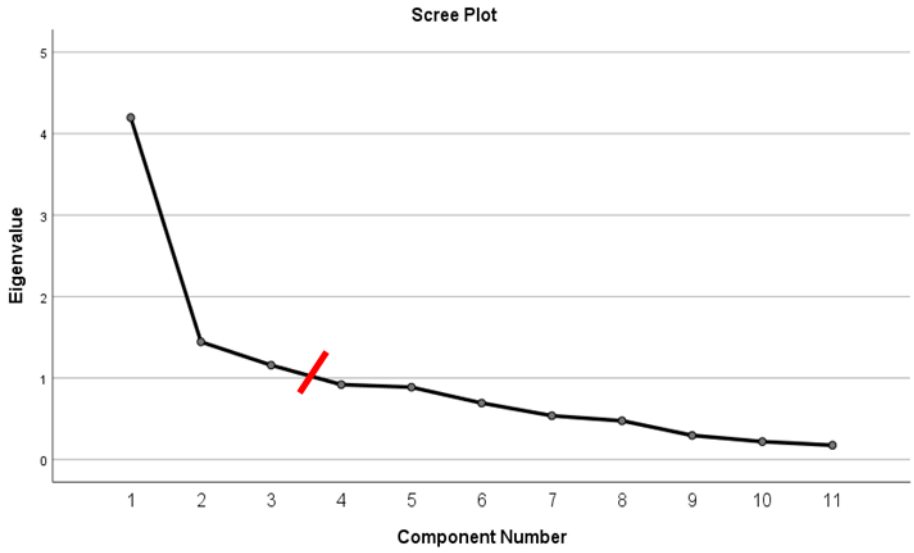

Figure S3.4. Scree-plot of eigenvalues for PCA factors.

3.4.8 Moderation of PCA factors on the within-subject association between VS reactivity and affective reactivity to positive events

To explore whether the higher order dimensional factors derived from the PCA of psychological and social environmental measures at baseline assessment moderate the within-subject association between VS reactivity and real-life affective reactivity to positive events, we tested whether the interaction between affective reactivity to positive events and each PCA factor scores predicts VS reactivity in the multilevel analyses. For example, if we tested the moderation of social environmental risk on the association between VS reactivity and affective reactivity to positive events, the equation for this multilevel model was as follows:

Equation S3.4:

$$
\begin{aligned}
&Y(\boldsymbol{VS\ reactivity})_{ij} \\
&\quad = \beta_{00} + \beta_{10} * age_{ij} + \beta_{20} * sex_j + \beta_{30} \\
&\quad * affective\ reactivity\ to\ positive\ events_{ij} + \beta_{40} \\
&\quad * social\ environmental\ risk_j + \boldsymbol{\beta_{50}} \\
&\quad * \boldsymbol{affective\ reactivity\ to\ positive\ events_{ij}} \\
&\quad * \boldsymbol{social\ environmental\ risk_j} + u_{0j} + r_{ij}
\end{aligned}
$$

4 DISCUSSION

Sustained low affective well-being is a contributing risk factor for the emergence and maintenance of psychiatric symptoms. Thus, understanding how to improve daily-life affective well-being is an important issue in psychiatry research that may help to increase resilience against psychiatric disorders in the long run. Previous studies have identified several real-life resilience resources for affective well-being including social contact (Hefner & Eisenberg, 2009), positive experiences (Doorley et al., 2020; Grosse Rueschkamp et al., 2020), physical activity (Kanning & Schlicht, 2010; Liao et al., 2015; Reichert et al., 2020; Wichers et al., 2012), and green space exposure (Bratman et al., 2015; Tost et al., 2019; White et al., 2013). Unlike physical activity and green space exposure, which have been widely studied, the neural bases of affective reactivity to social contact and to positive events remain unclear. In this dissertation, I investigated the neural correlates of two affective resilience measures, social affective benefit and affective reactivity to positive events, and probed their relevance for psychiatric risk and resilience using a multimodal approach combining smartphone-based ambulatory assessment, MRI, as well as social and psychological risk measures for psychiatric disorders.

4.1 The neural basis of social affective benefit and implications for psychiatric resilience

In study 1, we showed robust associations between real-life social contact and increased momentary affect in healthy adults in two independent samples, thus confirming that social contact is a real-life resilience resource contributing to affective well-being in daily life. We further validated that higher social affective benefit in daily life was associated with increased social competence, a composite measure indicating the ability to cope by seeking social support and the possession of socially desirable personality traits such as agreeableness and conscientiousness. Notably, the ability to cope by seeking social support has been linked to better mental health in nursing students (Montes-Berges & Augusto, 2007), early adolescents (Plancherel & Bolognini, 1995), and female victims of intimate partner violence (Kocot & Goodman, 2003). Moreover, coping by utilizing social support was identified as a protective factor against depression (Roohafza et al., 2014) and relapse in schizophrenia patients (Hultman, Wieselgren, & Öhman, 1997). One prominent theory explaining the

relationship between coping by seeking social support and mental health is the social buffering hypothesis, which argues that social support contributes to mental health mainly by buffering the adverse effects of stressors (Cohen & Wills, 1985; Holt-Lunstad et al., 2010; Mitchell et al., 1982). Apart from social coping, two socially desirable personality traits belonging to the Big Five personality traits (Goldberg, 1990), conscientiousness and agreeableness, also contributed to the social competence composite measure.

Agreeableness is a construct describing a set of characteristics linked to an interpersonal tendency towards altruism and cooperating with others (Graziano & Eisenberg, 1997). Agreeableness is of fundamental importance for affective well-being and mental health mainly due to the fact that people with higher agreeableness are less likely to experience interpersonal conflicts with others which may induce negative feelings and stress (Jensen-Campbell & Graziano, 2001). Conscientiousness is “a spectrum of constructs that describe individual differences in the propensity to be self-controlled, responsible to others, hardworking, orderly, and rule abiding” (Roberts, Lejuez, Krueger, Richards, & Hill, 2014). High levels of conscientiousness have been closely linked to resilience in healthy adolescents (Nakaya et al., 2006), which was confirmed recently by a meta-analysis comprising 32 studies with 15609 participants (Oshio et al., 2018). In contrast, low conscientiousness is an important predictor of depression beyond other mental health determinants like neuroticism and socioeconomic status (Kendler & Myers, 2010). Thus, taken together we showed in study 1 that social affective benefit is related to a social competence measure that has important implications for psychological resilience and mental health. Moreover, a previous study on psychology students showed that social anhedonic individuals, who are considered to demonstrate deficient need to belong, profited less from social contact in daily life (Kwapil et al., 2009). Further evidence from the clinical domain demonstrates that schizophrenia patients with increased social affective benefit exhibited less severe negative symptoms (Oorschot et al., 2013) highlighting the role of social affective benefit for psychiatric resilience. Given our findings in community-based samples and previous findings in clinical cohorts, we argue that social affective benefit may represent a real-life affective resilience measure for mental health in the community and the clinical domain. Notably, in study 2 our healthy individuals tend to spend time mostly with people they like (>90% of “in company” events). In future studies, it would thus be interesting to better understand whether being in contact with

individuals who people do not like (e.g., at work, at school) will alter affective well-being and if such an effect would be linked rather to psychiatric risk than resilience.

The neuroimaging findings of study 1 linked enhanced daily-life social affective benefit to larger gray matter volume in the transition area between the dorsal and perigenual ACC. Our findings thus confirmed my hypothesis that social affective benefit maps to the structural integrity of the ACC. The location fits with a framework suggesting that the transition area between the dorsal and perigenual ACC adopts an integrative function (Etkin et al., 2011), in comparison with the traditional view that the ACC can be split into dorsal-cognitive vs. ventral-affective subregions (Bush et al., 2000). In fact, previous literature showed that the dorsal and perigenual ACC maintain dense anatomical connections (Beckmann et al., 2009; Johansen-Berg et al., 2008) and receive overlapping anatomical inputs (Tang et al., 2019). These two subregions are also functionally interconnected during resting state (Margulies et al., 2007) and when experiencing social stress (Akdeniz et al., 2014b). Moreover, the dorsal and perigenual ACC are linked to a variety of social-cognitive-emotional functions including negative emotion processing (Vogt, 2005), social distress processing (Eisenberger, 2012), as well as person perception and mentalizing during social interaction (Amodio & Frith, 2006). Consequently, our data suggest that the structural integrity of the dorsal and perigenual ACC is essential for the integration of social information and emotional information during social interactions (Adolphs, 2009; Apps et al., 2016; Etkin et al., 2011).

As discussed in the general introduction, the ACC has been considered as a neural convergence site for social environmental risk factors that have previously been associated with a vulnerability for psychiatric disorders (Akdeniz et al., 2014b; Ansell, Rando, Tuit, Guarnaccia, & Sinha, 2012; Cohen et al., 2006; Gianaros et al., 2007; Lederbogen et al., 2011; Zink et al., 2008). Scientists have proposed that the critical role of ACC in the regulation of the hypothalamic-pituitary-adrenal (HPA) axis underpins the established associations between alterations of the ACC structure and function and social environmental stressors (Diorio, Viau, & Meaney, 1993). This idea was supported by recent studies showing that higher stress-related activity in the ACC was related to both decreased cortisol awakening response (Boehringer et al., 2015) and reduced stress-induced cortisol release (Sinha, Lacadie, Constable, & Seo, 2016). Similar to the role of the ACC in the link from social environmental risk factors to the vulnerability for psychiatric disorders, protective factors may also exert influences on

the ACC to buffer the adverse effects of stressors. For example, here our data linked a real-life affective resilience measure to higher ACC gray matter volume. Likewise, Holz et al. (2016) argued that positive stress coping styles (i.e., stress-reducing) were related to increased ACC gray matter volume. Consistently, increased perigenual ACC gray matter volume was associated with higher perceived social status (Gianaros et al., 2007), which is typically considered to be a resilience factor against stressful experiences. Moreover, ACC cortical thickness was positively related to self-reported resilience in healthy individuals (Gupta et al., 2017). Taken together, these studies suggest that the structural integrity of the ACC may be inherent to the concept of resilience. In addition to associations between resilience factors and ACC structure, Eisenberger and colleagues (2007) reported that greater daily-life social support and reduced stress-induced cortisol responses in the laboratory were associated with blunted activity in the dorsal ACC during social stress processing. Importantly, the blunted ACC activity mediated the relationship between higher daily-life social support and lower cortisol responses. These findings suggest that ACC functioning during social stress may underpin the relationship between social environmental resilience factors and reduced neuroendocrine stress responses indicating low vulnerability for major psychiatric disorders (Berger et al., 2016; Zorn et al., 2017). In summary, evidence highlighting associations between social stress and ACC functional and structural integrity provides mechanistic hints that social affective benefit might contribute to mental health via stress regulatory neural circuits that include the ACC.

4.2 The neural basis of affective reactivity to positive events and implications for psychiatric resilience

Study 2 highlighted positive events as another real-life resilience resource that contributed to increased affective well-being in daily life. As expected based on findings from previous ambulatory assessment studies (Grosse Rueschkamp et al., 2020; Peeters et al., 2003), separate multilevel models consistently revealed that higher positive event intensity was associated with increased positive affect at all three time points. In line with previous work, this finding underlines that positive events are a real-life resource for mitigating low mood in a community-based cohort, an effect previously reported in patients with major depression (Peeters et al., 2003), as well as in healthy adolescents and young adults with overall low mood (Grosse Rueschkamp et al., 2020). Importantly, we demonstrated in the between-subject neuroimaging analysis

that VS reward-related reactivity was linked to affective reactivity to positive events at baseline, indicating that VS reward-related reactivity might be a potential neurobiological substrate of affective reactivity to positive events.

The localization of this neuroimaging finding fits with previous literature that suggested a relationship between other real-life measures of reward-related experiences and striatal reward-related functioning (Forbes et al., 2009; Forbes et al., 2010; Heller et al., 2015; Kasanova et al., 2017; Kasanova et al., 2018a; Moran et al., 2019). Further, compared to the existing work, study 2 linked VS reactivity during reward anticipation to affective reactivity to positive events, two well-documented phenotypes for psychiatric disorders (Bylsma et al., 2011; Grosse Rueschkamp et al., 2020; Peeters et al., 2003; Wichers et al., 2010). Notably, study 2 extends the cross-sectional baseline results by showing that elevated affective reactivity to positive events was associated with increased VS reactivity within subjects at any time point. This finding suggests that these two reward-related measures from real-life ambulatory assessments and laboratory-based neuroimaging co-evolve over time. Importantly, the within-subject association was not influenced by age or age-squared, suggesting that the within-subject association was independent of a previously reported inverted U-shaped developmental effect of VS reactivity (Braams et al., 2015; Schreuders et al., 2021).

Moreover, the within-subject relationship between VS reactivity and affective reactivity to positive events was moderated by social environmental risk, a composite higher-order measure indicated by urban upbringing scores and social network sizes. This finding thus suggests that affective reactivity to positive events and VS reactivity co-evolve over time, specifically in individuals who were raised in big cities and who have smaller social networks, two previously discussed social environmental risk factors for psychiatric disorders (Meyer-Lindenberg & Tost, 2012; Selten et al., 2013). Given previous work showing the role of affective reactivity to positive events for resilience against psychiatric disorders (Bylsma et al., 2011; Khazanov et al., 2019; Peeters et al., 2003), we speculate that for individuals with high social environmental risk, the enjoyment of positive experiences in daily life may be an important real-life affective resilience measure to compensate for reduced VS reactivity, a well-known neural phenotype for psychiatric disorders (Dichter et al., 2012; Keren et al., 2018; Radua et al., 2015; Schwarz et al., 2020).

4.3 Evaluation of the methodological aspects

4.3.1 Strengths

The studies presented in my dissertation have several strengths. First, in both studies, daily-life affective well-being was assessed with ambulatory assessment instead of retrospective methods. As discussed in the introduction section, using ambulatory assessment can improve ecological validity, capture individuals' momentary states in real-time, and track the dynamic process of momentary affect (Ebner-Priemer & Trull, 2009; Trull & Ebner-Priemer, 2013). Moreover, ambulatory assessment enables us to collect social environmental information and affective well-being simultaneously, thus allow us to examine the interactions between momentary affect and daily-life activities (e.g., positive events, physical activity), social situations (e.g., social contact), and environmental factors (e.g., green space exposure).

Second, both studies of this dissertation recruited healthy participants from local communities. Choosing healthy community-based individuals with no history of psychiatric disorders allows us to identify neurobiological substrates of real-life affective resilience measures while preventing possible confounding effects of diseases and medication. The community-based sample also highlights the epidemiological importance of our findings for psychiatry and positive psychology research since positive valence is recognized as a dimensional continuum of psychopathologically relevant behaviors across health and disease in the RDoC framework (Insel et al., 2010).

Third, given the dramatic changes in subcortical dopaminergic systems during adolescence and early adulthood and its implications for the pathophysiology of major psychiatric disorders that appear during this time (Wahlstrom, Collins, White, & Luciana, 2010; Wahlstrom, White, & Luciana, 2010), the second study adopted an accelerated longitudinal design to acquire ambulatory assessment and fMRI data over three measurement time points in a sample of adolescents and young adults. The longitudinal data allowed us to test and control for the potential influence of the development effect of striatal reward processing when examining the neural correlates of affective reactivity to positive events.

4.3.2 Limitations and future directions

This dissertation has several limitations worth noting. First, even in large community-based epidemiological studies, potential sample bias cannot be excluded because

non-response might be inter-correlated with characteristics of interest (Little, Lewitzky, Heeringa, Lepkowski, & Kessler, 1997). The problem is more concerning when a longitudinal approach is used (e.g., study 2 of this dissertation) because of decreasing rates of participation over time, namely dropout bias (Drivsholm et al., 2006). Consequently, the generalizability of the dissertation's findings to a broader population is undermined due to the compromised representativeness. To account for the possible differences in target variables between participants and non-participants, scientists usually employ weighting adjustments (i.e., endow different weights for individuals according to the probability of participation, followed by trimming and standardization) (Little et al., 1997; Schmidt & Woll, 2017).

Second, when testing the associations between social contact/positive event intensity and momentary affect with ambulatory assessment data, the concurrent measurement of momentary affect and social contact information/positive event intensity restrains our inferences on any causal effect of the associations. It is possible that momentary affect increases in response to the social contact/positive events, or a more positive affect motivates individuals to seek out social contact or increases the probability of positive events. Future studies employing time-lagged analyses to check whether the current affective states would predict future social contact information and positive event intensity could help make stronger arguments about the directionality of effects. The observational study designs employed in study 1 and study 2 also limit any causal implications of the association between real-life affective resilience measures (i.e., social affective benefit, affective reactivity to positive events) and corresponding brain measures (i.e., ACC gray matter volume and VS reactivity during reward processing). While we cannot establish causal relationships, we speculate that real-life affective resilience measures contribute to the changes in brain structure and function given existing evidence on the causal influence of social environmental exposures (e.g., urban green space, nature experience, social network size) on brain structure and functions (Bratman et al., 2015; Sallet et al., 2011; Tost et al., 2019). However, further experiments are needed to clarify whether manipulating real-life affective resilience measures influences brain structure and function in the long run and thus has the potential to improve psychiatric conditions.

Third, previous studies on social affective benefit and affective reactivity to positive events demonstrated differences between healthy individuals and psychiatric patients (Bylsma et al., 2011; Khazanov et al., 2019; Peeters et al., 2003), while here we only

studied healthy participants. So, it is still unknown whether the neural substrates of social affective benefit and affective reactivity to positive events differ in psychiatric patients compared to healthy controls. Future studies are needed to investigate potential qualitative differences in the biological underpinnings of social affective benefit and affective reactivity to positive events between healthy populations and psychiatric patients with pronounced social functioning impairments and reward processing deficits.

4.4 Outlook

My dissertation highlights the relevance of two real-life affective resilience measures, social affective benefit and affective reactivity to positive events for psychiatric risk and resilience, and provides the first empirical evidence for the respective underlying neurobiological substrates. The findings from my dissertation may contribute to mental health interventions geared towards individuals with high risk for psychiatric conditions (i.e., lower affective well-being in daily life). In particular, mobile health technologies could contribute to motivating individuals with low mood to seek more social contacts and positive experiences in daily life. Moreover, such mobile health interventions can contribute to collecting more detailed information of individuals' daily-life activities to identify under which social circumstances or positive experiences the affective well-being is boosted the most. For example, when participants are in company, the feeling of belonging to the surroundings may promote social affective benefit. Using individualized mobile health technologies, it is possible to detect beneficial social circumstances and positive experiences and thus precisely deliver manipulations to prevent the development of severe affective symptoms in at-risk populations.

Although my dissertation was conducted in healthy individuals, the findings can provide insights into the treatment of psychiatric patients. First, the identified real-life affective resilience measures may help predict the development of psychopathological symptoms. For example, affective reactivity to positive events has been shown to improve the prediction of future recurrence of depressive symptomatology in remitted depressed subjects (Wichers et al., 2010). The study of real-life affective resilience measures can also help monitor treatment effects. In one study examining the association between momentary affect and social contact before treatment and the treatment effects in depressed patients, the authors found higher affective well-being and more time being with others predicted lower posttreatment severity and depressive symptoms (Forbes et al., 2012). Taken together, my dissertation highlights the

potential of daily-life resilience measures for predicting the development of low affective well-being in at-risk populations and treatment effects in psychiatric patients.

5 SUMMARY

Disturbed affective well-being contributes to the development of major psychiatric disorders. Thus, scientists and clinicians have been investigating how to help psychiatric patients and at-risk populations become resilient against distressed affective states. In the present dissertation, I studied two real-life affective resilience measures, namely social affective benefit and affective reactivity to positive events that capture the respective effects of social contact and positive events on real-life affective well-being. To this end, I used a neuro-epidemiological approach combining state-of-the-art smartphone-based ambulatory assessment, neuroimaging, and self-report inventories of psychiatric risk and resilience. I examined the neurobiological correlates of social affective benefit using structural MRI in study 1, and the neural basis of affective reactivity to positive events using functional MRI measured with the monetary incentive delay task in study 2. Additionally, in both studies, I also probed the potential relevance of these two real-life affective resilience measures for psychiatric risk and resilience.

In study 1, I corroborated in two independent community-based adult samples that real-life social contact was associated with increased affective valence using multilevel models, an effect I named as social affective benefit. Our findings also showed that higher levels of social affective benefit were associated with greater anterior cingulate cortex gray matter volume, suggesting that structural integrity of the anterior cingulate cortex may be important for this fundamental affective resilience measure. Moreover, higher levels of social affective benefit were linked to increased social competence, indicated by the ability of social coping in stressful life situations and socially desirable personality traits such as agreeableness and conscientiousness. Together these findings demonstrate that social affective benefit may be relevant for psychiatric resilience.

In study 2, I showed a strong association between real-life positive events and momentary affect in a community-based developmental sample comprising adolescents and young adults. Further, affective reactivity to positive events was linked to laboratory-based reward-related ventral striatum reactivity at the between-subject level. Additionally, using an accelerated longitudinal design, I demonstrated that ventral striatum reactivity was linearly associated with real-life affective reactivity to

positive events within subjects across three annually separated measurement time points. This within-subject association indicates that real-life and laboratory-based neural reward measures co-evolve over time, which was specifically pronounced in individuals with high social environmental risk indicated by higher urban upbringing scores and a smaller social network size. I speculated that for at-risk individuals, the ability to benefit from rewarding experiences may represent an important real-life resilience measure to compensate for compromised striatal reward processing. Moreover, I showed that the within-subject association between ventral striatum reactivity and affective reactivity to positive events was independent of the developmental effect of striatal reward processing in adolescence and early adulthood.

In summary, beneficial social influences and positive daily-life experiences are major sources of mental health resilience. This dissertation suggests that social contact and positive events are strongly associated with enhanced affective well-being in real life, thus forming two real-life affective resilience measures: social affective benefit and affective reactivity to positive events. The neurobiological substrates of social affective benefit and affective reactivity to positive events map to a region shown as a convergence site for psychiatric resilience and a core region in the brain reward system that is often perturbed in psychiatric patients. Given the technological advances in mobile research and intervention technologies, real-life social affective benefit and affective reactivity to positive events may thus represent important and feasible targets for smartphone-based preventative and therapeutic interventions aiming at identifying and utilizing daily life experiences to reduce the mental health risk in vulnerable populations and mitigating affective symptoms in psychiatric patients.

6 REFERENCES

Adler, N. E., Epel, E. S., Castellazzo, G., & Ickovics, J. R. (2000). Relationship of subjective and objective social status with psychological and physiological functioning: preliminary data in healthy white women. *Health Psychology, 19*(6), 586-592. doi:10.1037//0278-6133.19.6.586

Adolphs, R. (2009). The social brain: neural basis of social knowledge. *Annual Review of Psychology, 60*, 693-716. doi:10.1146/annurev.psych.60.110707.163514

Akdeniz, C., Tost, H., & Meyer-Lindenberg, A. (2014a). The neurobiology of social environmental risk for schizophrenia: an evolving research field. *Social Psychiatry and Psychiatric Epidemiology, 49*(4), 507-517. doi:10.1007/s00127-014-0858-4

Akdeniz, C., Tost, H., Streit, F., Haddad, L., Wust, S., Schafer, A., . . . Meyer-Lindenberg, A. (2014b). Neuroimaging evidence for a role of neural social stress processing in ethnic minority-associated environmental risk. *JAMA Psychiatry, 71*(6), 672-680. doi:10.1001/jamapsychiatry.2014.35

Amodio, D. M., & Frith, C. D. (2006). Meeting of minds: the medial frontal cortex and social cognition. *Nature Reviews: Neuroscience, 7*(4), 268-277. doi:10.1038/nrn1884

Ansell, E. B., Rando, K., Tuit, K., Guarnaccia, J., & Sinha, R. (2012). Cumulative adversity and smaller gray matter volume in medial prefrontal, anterior cingulate, and insula regions. *Biological Psychiatry, 72*(1), 57-64. doi:10.1016/j.biopsych.2011.11.022

Apps, M. A., Rushworth, M. F., & Chang, S. W. (2016). The Anterior Cingulate Gyrus and Social Cognition: Tracking the Motivation of Others. *Neuron, 90*(4), 692-707. doi:10.1016/j.neuron.2016.04.018

Arias-Carrion, O., Stamelou, M., Murillo-Rodriguez, E., Menendez-Gonzalez, M., & Poppel, E. (2010). Dopaminergic reward system: a short integrative review. *International Archives of Medicine, 3*, 24. doi:10.1186/1755-7682-3-24

Arrondo, G., Segarra, N., Metastasio, A., Ziauddeen, H., Spencer, J., Reinders, N., . . . Murray, G. (2015). Reduction in ventral striatal activity when anticipating a reward in depression and schizophrenia: a replicated cross-diagnostic finding. *Frontiers in Psychology, 6*(1280). doi:10.3389/fpsyg.2015.01280

Arthurs, O. J., & Boniface, S. (2002). How well do we understand the neural origins of the fMRI BOLD signal? *Trends in Neurosciences, 25*(1), 27-31.

Ashburner, J., & Friston, K. J. (2000). Voxel-based morphometry--the methods. *NeuroImage, 11*(6 Pt 1), 805-821. doi:10.1006/nimg.2000.0582

Beckmann, M., Johansen-Berg, H., & Rushworth, M. F. (2009). Connectivity-based parcellation of human cingulate cortex and its relation to functional specialization. *Journal of Neuroscience, 29*(4), 1175-1190. doi:10.1523/JNEUROSCI.3328-08.2009

Behrens, T. E., Hunt, L. T., Woolrich, M. W., & Rushworth, M. F. (2008). Associative learning of social value. *Nature, 456*(7219), 245-249. doi:10.1038/nature07538

Berger, M., Kraeuter, A. K., Romanik, D., Malouf, P., Amminger, G. P., & Sarnyai, Z. (2016). Cortisol awakening response in patients with psychosis: Systematic review and meta-analysis. *Neurosci Biobehav Rev, 68*, 157-166. doi:10.1016/j.neubiorev.2016.05.027

Beutel, M. E., Klein, E. M., Brahler, E., Reiner, I., Junger, C., Michal, M., . . . Tibubos, A. N. (2017). Loneliness in the general population: prevalence, determinants

and relations to mental health. *BMC Psychiatry, 17*(1), 97. doi:10.1186/s12888-017-1262-x

Bickart, K. C., Wright, C. I., Dautoff, R. J., Dickerson, B. C., & Barrett, L. F. (2011). Amygdala volume and social network size in humans. *Nat Neurosci, 14*(2), 163-164. doi:10.1038/nn.2724

Birn, R. M., Cox, R. W., & Bandettini, P. A. (2002). Detection versus estimation in event-related fMRI: choosing the optimal stimulus timing. *NeuroImage, 15*(1), 252-264. doi:10.1006/nimg.2001.0964

Blakemore, S. J. (2008). The social brain in adolescence. *Nature Reviews: Neuroscience, 9*(4), 267-277. doi:10.1038/nrn2353

Boehringer, A., Tost, H., Haddad, L., Lederbogen, F., Wüst, S., Schwarz, E., & Meyer-Lindenberg, A. (2015). Neural Correlates of the Cortisol Awakening Response in Humans. *Neuropsychopharmacology, 40*(9), 2278-2285. doi:10.1038/npp.2015.77

Bolger, N., & Laurenceau, J.-P. (2013). *Intensive longitudinal methods: An introduction to diary and experience sampling research*. New York: The Guilford Press.

Borkenau, P., & Ostendorf, F. (2008). *NEO-FFI : NEO-Fünf-Faktoren-Inventar nach Costa und McCrae* (2 ed.). Göttingen: Hogrefe.

Braams, B. R., van Duijvenvoorde, A. C., Peper, J. S., & Crone, E. A. (2015). Longitudinal changes in adolescent risk-taking: a comprehensive study of neural responses to rewards, pubertal development, and risk-taking behavior. *Journal of Neuroscience, 35*(18), 7226-7238. doi:10.1523/JNEUROSCI.4764-14.2015

Bratman, G. N., Hamilton, J. P., Hahn, K. S., Daily, G. C., & Gross, J. J. (2015). Nature experience reduces rumination and subgenual prefrontal cortex activation. *Proceedings of the National Academy of Sciences of the United States of America, 112*(28), 8567-8572. doi:10.1073/pnas.1510459112

Brown, L. H., Silvia, P. J., Myin-Germeys, I., & Kwapil, T. R. (2007). When the need to belong goes wrong: the expression of social anhedonia and social anxiety in daily life. *Psychol Sci, 18*(9), 778-782. doi:10.1111/j.1467-9280.2007.01978.x

Bush, G., Frazier, J. A., Rauch, S. L., Seidman, L. J., Whalen, P. J., Jenike, M. A., . . . Biederman, J. (1999). Anterior cingulate cortex dysfunction in attention-deficit/hyperactivity disorder revealed by fMRI and the Counting Stroop. *Biological Psychiatry, 45*(12), 1542-1552. doi:10.1016/s0006-3223(99)00083-9

Bush, G., Luu, P., & Posner, M. I. (2000). Cognitive and emotional influences in anterior cingulate cortex. *Trends in Cognitive Sciences, 4*(6), 215-222. doi:10.1016/s1364-6613(00)01483-2

Bush, G., Vogt, B. A., Holmes, J., Dale, A. M., Greve, D., Jenike, M. A., & Rosen, B. R. (2002). Dorsal anterior cingulate cortex: a role in reward-based decision making. *Proceedings of the National Academy of Sciences of the United States of America, 99*(1), 523-528. doi:10.1073/pnas.012470999

Bylsma, L. M., Taylor-Clift, A., & Rottenberg, J. (2011). Emotional reactivity to daily events in major and minor depression. *Journal of Abnormal Psychology, 120*(1), 155-167. doi:10.1037/a0021662

Cacioppo, J. T., Hughes, M. E., Waite, L. J., Hawkley, L. C., & Thisted, R. A. (2006). Loneliness as a specific risk factor for depressive symptoms: cross-sectional and longitudinal analyses. *Psychology and Aging, 21*(1), 140-151. doi:10.1037/0882-7974.21.1.140

Carter, C. S., Botvinick, M. M., & Cohen, J. D. (1999). The contribution of the anterior cingulate cortex to executive processes in cognition. *Reviews in the Neurosciences, 10*(1), 49-57. doi:10.1515/revneuro.1999.10.1.49

Carver, C. S. (1997). You want to measure coping but your protocol's too long: consider the brief COPE. *International Journal of Behavioral Medicine, 4*(1), 92-100. doi:10.1207/s15327558ijbm0401_6

Carver, C. S., Scheier, M. F., & Segerstrom, S. C. (2010). Optimism. *Clinical Psychology Review, 30*(7), 879-889. doi:10.1016/j.cpr.2010.01.006

Carver, C. S., Scheier, M. F., & Weintraub, J. K. (1989). Assessing coping strategies: a theoretically based approach. *Journal of Personality and Social Psychology, 56*(2), 267-283. doi:10.1037//0022-3514.56.2.267

Coan, J. A., Schaefer, H. S., & Davidson, R. J. (2006). Lending a hand: social regulation of the neural response to threat. *Psychological Science, 17*(12), 1032-1039. doi:10.1111/j.1467-9280.2006.01832.x

Cohen, R. A., Grieve, S., Hoth, K. F., Paul, R. H., Sweet, L., Tate, D., . . . Williams, L. M. (2006). Early life stress and morphometry of the adult anterior cingulate cortex and caudate nuclei. *Biological Psychiatry, 59*(10), 975-982. doi:10.1016/j.biopsych.2005.12.016

Cohen, S., Doyle, W. J., Skoner, D. P., Rabin, B. S., & Gwaltney, J. M., Jr. (1997). Social ties and susceptibility to the common cold. *JAMA, 277*(24), 1940-1944.

Cohen, S., & Pressman, S. D. (2006). Positive affect and health. *Current directions in psychological science, 15*(3), 122-125.

Cohen, S., & Wills, T. A. (1985). Stress, social support, and the buffering hypothesis. *Psychological Bulletin, 98*(2), 310-357.

Cohn, M. A., Fredrickson, B. L., Brown, S. L., Mikels, J. A., & Conway, A. M. (2009). Happiness unpacked: positive emotions increase life satisfaction by building resilience. *Emotion, 9*(3), 361-368. doi:10.1037/a0015952

Collip, D., Oorschot, M., Thewissen, V., Van Os, J., Bentall, R., & Myin-Germeys, I. (2011). Social world interactions: how company connects to paranoia. *Psychological Medicine, 41*(5), 911-921. doi:10.1017/S0033291710001558

Csikszentmihalyi, M., & Larson, R. (1987). Validity and reliability of the Experience-Sampling Method. *Journal of Nervous and Mental Disease, 175*(9), 526-536. doi:10.1097/00005053-198709000-00004

Delgado, M. R. (2007). Reward-related responses in the human striatum. *Annals of the New York Academy of Sciences, 1104*(1), 70-88. doi:10.1196/annals.1390.002

Devinsky, O., Morrell, M. J., & Vogt, B. A. (1995). Contributions of anterior cingulate cortex to behaviour. *Brain, 118 (Pt 1)*, 279-306. doi:10.1093/brain/118.1.279

Dichter, G. S., Felder, J. N., Green, S. R., Rittenberg, A. M., Sasson, N. J., & Bodfish, J. W. (2012). Reward circuitry function in autism spectrum disorders. *Social Cognitive and Affective Neuroscience, 7*(2), 160-172. doi:10.1093/scan/nsq095

Diorio, D., Viau, V., & Meaney, M. (1993). The role of the medial prefrontal cortex (cingulate gyrus) in the regulation of hypothalamic-pituitary-adrenal responses to stress. *The Journal of Neuroscience, 13*(9), 3839-3847. doi:10.1523/jneurosci.13-09-03839.1993

Doorley, J. D., Goodman, F. R., Disabato, D. J., Kashdan, T. B., Weinstein, J. S., & Shackman, A. J. (2020). The momentary benefits of positive events for individuals with elevated social anxiety. *Emotion*. doi:10.1037/emo0000725

Döring, N., & Bortz, J. (1993). Psychometrische Einsamkeitsforschung: Deutsche Neukonstruktion der UCLA Loneliness Scale. *Diagnostica*.

Dornbach-Bender, A., Ruggero, C. J., Smith, P., Schuler, K., Bennett, C. B., Neumann, C. S., & Callahan, J. L. (2020). Association of behavioral activation system sensitivity to lower level facets of positive affect in daily life. *Personality and*

Individual Differences, 152, 109570. doi:https://doi.org/10.1016/j.paid.2019.109570

Drevets, W. C., & Raichle, M. E. (1998). Reciprocal suppression of regional cerebral blood flow during emotional versus higher cognitive processes: Implications for interactions between emotion and cognition. *Cognition and emotion*.

Drivsholm, T., Eplov, L. F., Davidsen, M., Jørgensen, T., Ibsen, H., Hollnagel, H., & Borch-Johnsen, K. (2006). Representativeness in population-based studies: A detailed description of non-response in a Danish cohort study. *Scandinavian Journal of Public Health, 34*(6), 623-631. doi:10.1080/14034940600607616

Ebner-Priemer, U. W., Eid, M., Kleindienst, N., Stabenow, S., & Trull, T. J. (2009). Analytic strategies for understanding affective (in)stability and other dynamic processes in psychopathology. *Journal of Abnormal Psychology, 118*(1), 195-202. doi:10.1037/a0014868

Ebner-Priemer, U. W., & Trull, T. J. (2009). Ecological momentary assessment of mood disorders and mood dysregulation. *Psychological Assessment, 21*(4), 463-475. doi:10.1037/a0017075

Eisenberger, N. I. (2012). The pain of social disconnection: examining the shared neural underpinnings of physical and social pain. *Nature Reviews: Neuroscience, 13*(6), 421-434. doi:10.1038/nrn3231

Eisenberger, N. I., Taylor, S. E., Gable, S. L., Hilmert, C. J., & Lieberman, M. D. (2007). Neural pathways link social support to attenuated neuroendocrine stress responses. *NeuroImage, 35*(4), 1601-1612. doi:10.1016/j.neuroimage.2007.01.038

Esslinger, C., Englisch, S., Inta, D., Rausch, F., Schirmbeck, F., Mier, D., . . . Zink, M. (2012). Ventral striatal activation during attribution of stimulus saliency and reward anticipation is correlated in unmedicated first episode schizophrenia patients. *Schizophrenia Research, 140*(1), 114-121. doi:https://doi.org/10.1016/j.schres.2012.06.025

Etkin, A., Egner, T., & Kalisch, R. (2011). Emotional processing in anterior cingulate and medial prefrontal cortex. *Trends in Cognitive Sciences, 15*(2), 85-93. doi:10.1016/j.tics.2010.11.004

Fahrenberg, J., Myrtek, M., Pawlik, K., & Perrez, M. (2007). Ambulatory Assessment - Monitoring Behavior in Daily Life Settings. *European Journal of Psychological Assessment, 23*(4), 206-213. doi:10.1027/1015-5759.23.4.206

Feng, C., Luo, Y. J., & Krueger, F. (2015). Neural signatures of fairness-related normative decision making in the ultimatum game: a coordinate-based meta-analysis. *Hum Brain Mapp, 36*(2), 591-602. doi:10.1002/hbm.22649

First, M., Spitzer, R., Gibbon, M., & Williams, J. (2001). *Structured Clinical Interview for DSM-IV-TR Axis I Disorders, Research Version, Patient Edition with Psychotic Screen (SCID-I/P W/ PSY SCREEN).* New York: New York Psychiatric Institute.

Forbes, E. E., Hariri, A. R., Martin, S. L., Silk, J. S., Moyles, D. L., Fisher, P. M., . . . Dahl, R. E. (2009). Altered striatal activation predicting real-world positive affect in adolescent major depressive disorder. *American Journal of Psychiatry, 166*(1), 64-73. doi:10.1176/appi.ajp.2008.07081336

Forbes, E. E., Ryan, N. D., Phillips, M. L., Manuck, S. B., Worthman, C. M., Moyles, D. L., . . . Dahl, R. E. (2010). Healthy adolescents' neural response to reward: associations with puberty, positive affect, and depressive symptoms. *Journal of the American Academy of Child and Adolescent Psychiatry, 49*(2), 162-172 e161-165. doi:10.1097/00004583-201002000-00010

Forbes, E. E., Stepp, S. D., Dahl, R. E., Ryan, N. D., Whalen, D., Axelson, D. A., . . . Silk, J. S. (2012). Real-World Affect and Social Context as Predictors of Treatment Response in Child and Adolescent Depression and Anxiety: An Ecological Momentary Assessment Study. *Journal of Child and Adolescent Psychopharmacology, 22*(1), 37-47. doi:10.1089/cap.2011.0085

Fredrickson, B. L. (2000). Extracting meaning from past affective experiences: The importance of peaks, ends, and specific emotions. *Cognition & Emotion, 14*(4), 577-606. doi:10.1080/026999300402808

Gan, G., Ma, R., Reichert, M., Giurgiu, M., Ebner-Priemer, U. W., Meyer-Lindenberg, A., & Tost, H. (2021). Neural Correlates of Affective Benefit From Real-life Social Contact and Implications for Psychiatric Resilience. *JAMA psychiatry*. doi:10.1001/jamapsychiatry.2021.0560

Geschwind, N., Peeters, F., Jacobs, N., Delespaul, P., Derom, C., Thiery, E., . . . Wichers, M. (2010). Meeting risk with resilience: high daily life reward experience preserves mental health. *Acta Psychiatrica Scandinavica, 122*(2), 129-138. doi:10.1111/j.1600-0447.2009.01525.x

Gianaros, P. J., Horenstein, J. A., Cohen, S., Matthews, K. A., Brown, S. M., Flory, J. D., . . . Hariri, A. R. (2007). Perigenual anterior cingulate morphology covaries with perceived social standing. *Social Cognitive and Affective Neuroscience, 2*(3), 161-173. doi:10.1093/scan/nsm013

Giurgiu, M., Koch, E. D., Ottenbacher, J., Plotnikoff, R. C., Ebner-Priemer, U. W., & Reichert, M. (2019). Sedentary behavior in everyday life relates negatively to mood: An ambulatory assessment study. *Scand J Med Sci Sports, 29*(9), 1340-1351. doi:10.1111/sms.13448

Glaesmer, H., Grande, G., Braehler, E., & Roth, M. (2011). The German Version of the Satisfaction With Life Scale (SWLS). *Eur J Psychol Assess, 27*(2), 127-132. doi:10.1027/1015-5759/a000058

Goldberg, L. R. (1990). An alternative" description of personality": the big-five factor structure. *Journal of personality and social psychology, 59*(6), 1216.

Goodman, E., Adler, N. E., Kawachi, I., Frazier, A. L., Huang, B., & Colditz, G. A. (2001). Adolescents' Perceptions of Social Status: Development and Evaluation of a New Indicator. *Pediatrics, 108*(2), e31-e31. doi:10.1542/peds.108.2.e31

Graziano, W. G., & Eisenberg, N. (1997). Chapter 30 - Agreeableness: A Dimension of Personality. In R. Hogan, J. Johnson, & S. Briggs (Eds.), *Handbook of Personality Psychology* (pp. 795-824). San Diego: Academic Press.

Grimm, O., Heinz, A., Walter, H., Kirsch, P., Erk, S., Haddad, L., . . . Meyer-Lindenberg, A. (2014). Striatal response to reward anticipation: evidence for a systems-level intermediate phenotype for schizophrenia. *JAMA psychiatry, 71*(5), 531-539. doi:10.1001/jamapsychiatry.2014.9

Grosse Rueschkamp, J. M., Kuppens, P., Riediger, M., Blanke, E. S., & Brose, A. (2020). Higher well-being is related to reduced affective reactivity to positive events in daily life. *Emotion, 20*(3), 376-390. doi:10.1037/emo0000557

Gupta, A., Love, A., Kilpatrick, L. A., Labus, J. S., Bhatt, R., Chang, L., . . . Mayer, E. A. (2017). Morphological brain measures of cortico-limbic inhibition related to resilience. *Journal of Neuroscience Research, 95*(9), 1760-1775. doi:10.1002/jnr.24007

Haddad, L., Schafer, A., Streit, F., Lederbogen, F., Grimm, O., Wust, S., . . . Meyer-Lindenberg, A. (2015). Brain structure correlates of urban upbringing, an environmental risk factor for schizophrenia. *Schizophr Bull, 41*(1), 115-122. doi:10.1093/schbul/sbu072

Hagele, C., Schlagenhauf, F., Rapp, M., Sterzer, P., Beck, A., Bermpohl, F., . . . Heinz, A. (2015). Dimensional psychiatry: reward dysfunction and depressive mood across psychiatric disorders. *Psychopharmacology (Berl), 232*(2), 331-341. doi:10.1007/s00213-014-3662-7

Hannöver, W., Michael, A., Meyer, C., Rumpf, H.-J., Hapke, U., & John, U. (2004). Die Sense of coherence Scale von Antonovsky und das Vorliegen einer psychiatrischen Diagnose. *PPmP-Psychotherapie· Psychosomatik· Medizinische Psychologie, 54*(03/04), 179-186.

Hefner, J., & Eisenberg, D. (2009). Social support and mental health among college students. *American Journal of Orthopsychiatry, 79*(4), 491-499. doi:10.1037/a0016918

Heller, A. S., Fox, A. S., Wing, E. K., McQuisition, K. M., Vack, N. J., & Davidson, R. J. (2015). The Neurodynamics of Affect in the Laboratory Predicts Persistence of Real-World Emotional Responses. *Journal of Neuroscience, 35*(29), 10503-10509. doi:10.1523/JNEUROSCI.0569-15.2015

Herbert, T. B., & Cohen, S. (1993). Depression and immunity: a meta-analytic review. *Psychological Bulletin, 113*(3), 472-486. doi:10.1037/0033-2909.113.3.472

Herzberg, P. Y., Glaesmer, H., & Hoyer, J. (2006). Separating optimism and pessimism: a robust psychometric analysis of the revised Life Orientation Test (LOT-R). *Psychological Assessment, 18*(4), 433-438. doi:10.1037/1040-3590.18.4.433

Heubeck, B. G., & Boulter, E. (2021). PANAS Models of Positive and Negative Affectivity for Adolescent Boys. *Psychological Reports, 124*(1), 240-247. doi:10.1177/0033294120905512

Hoebel, J., Müters, S., Kuntz, B., Lange, C., & Lampert, T. (2015). Messung des subjektiven sozialen Status in der Gesundheitsforschung mit einer deutschen Version der MacArthur Scale. *Bundesgesundheitsblatt - Gesundheitsforschung - Gesundheitsschutz, 58*(7), 749-757. doi:10.1007/s00103-015-2166-x

Holt-Lunstad, J., Smith, T. B., & Layton, J. B. (2010). Social relationships and mortality risk: a meta-analytic review. *PLoS Med, 7*(7), e1000316. doi:10.1371/journal.pmed.1000316

Holz, N. E., Boecker, R., Jennen-Steinmetz, C., Buchmann, A. F., Blomeyer, D., Baumeister, S., . . . Laucht, M. (2016). Positive coping styles and perigenual ACC volume: two related mechanisms for conferring resilience? *Social Cognitive and Affective Neuroscience, 11*(5), 813-820. doi:10.1093/scan/nsw005

Holz, N. E., Tost, H., & Meyer-Lindenberg, A. (2020). Resilience and the brain: a key role for regulatory circuits linked to social stress and support. *Molecular Psychiatry, 25*(2), 379-396. doi:10.1038/s41380-019-0551-9

Huettel, S. A. (2012). Event-related fMRI in cognition. *NeuroImage, 62*(2), 1152-1156. doi:10.1016/j.neuroimage.2011.08.113

Huettel, S. A., Song, A. W., & McCarthy, G. (2004). *Functional magnetic resonance imaging* (Vol. 1): Sinauer Associates Sunderland.

Hughes, A. A., & Kendall, P. C. (2009). Psychometric properties of the Positive and Negative Affect Scale for Children (PANAS-C) in children with anxiety disorders. *Child Psychiatry and Human Development, 40*(3), 343-352.

Hultman, C. M., Wieselgren, I.-M., & Öhman, A. (1997). Relationships Between Social Support, Social Coping and Life Events in the Relapse of Schizophrenic Patients. *Scandinavian Journal of Psychology, 38*(1), 3-13. doi:https://doi.org/10.1111/1467-9450.00002

Hundt, N. E., Brown, L. H., Kimbrel, N. A., Walsh, M. A., Nelson-Gray, R., & Kwapil, T. R. (2013). Reinforcement sensitivity theory predicts positive and negative affect in daily life. *Personality and Individual Differences, 54*(3), 350-354. doi:10.1016/j.paid.2012.09.021

Husky, M. M., Grondin, O. S., & Swendsen, J. D. (2004). The relation between social behavior and negative affect in psychosis-prone individuals: an experience sampling investigation. *Eur Psychiatry, 19*(1), 1-7. doi:10.1016/j.eurpsy.2003.09.006

Insel, T., Cuthbert, B., Garvey, M., Heinssen, R., Pine, D. S., Quinn, K., . . . Wang, P. (2010). Research domain criteria (RDoC): toward a new classification framework for research on mental disorders. *American Journal of Psychiatry, 167*(7), 748-751. doi:10.1176/appi.ajp.2010.09091379

Jensen-Campbell, L. A., & Graziano, W. G. (2001). Agreeableness as a moderator of interpersonal conflict. *Journal of Personality, 69*(2), 323-362.

Jerusalem, M., & Schwarzer, R. (1992). Self-efficacy as a resource factor in stress appraisal processes. *Self-efficacy: Thought control of action, 195213*.

Johansen-Berg, H., Gutman, D. A., Behrens, T. E., Matthews, P. M., Rushworth, M. F., Katz, E., . . . Mayberg, H. S. (2008). Anatomical connectivity of the subgenual cingulate region targeted with deep brain stimulation for treatment-resistant depression. *Cerebral Cortex, 18*(6), 1374-1383. doi:10.1093/cercor/bhm167

Kahneman, D., Krueger, A. B., Schkade, D. A., Schwarz, N., & Stone, A. A. (2004). A survey method for characterizing daily life experience: the day reconstruction method. *Science, 306*(5702), 1776-1780. doi:10.1126/science.1103572

Kalisch, R., Muller, M. B., & Tuscher, O. (2015). A conceptual framework for the neurobiological study of resilience. *Behavioral and Brain Sciences, 38*, e92. doi:10.1017/S0140525X1400082X

Kanning, M. (2012). Using objective, real-time measures to investigate the effect of actual physical activity on affective States in everyday life differentiating the contexts of working and leisure time in a sample with students. *Front Psychol, 3*, 602. doi:10.3389/fpsyg.2012.00602

Kanning, M., & Schlicht, W. (2010). Be active and become happy: an ecological momentary assessment of physical activity and mood. *Journal of Sport and Exercise Psychology, 32*(2), 253-261.

Kaplan, G. A., & Reynolds, P. (1988). Depression and cancer mortality and morbidity: prospective evidence from the Alameda County study. *Journal of Behavioral Medicine, 11*(1), 1-13. doi:10.1007/BF00846165

Kasanova, Z., Ceccarini, J., Frank, M. J., Amelsvoort, T. V., Booij, J., Heinzel, A., . . . Myin-Germeys, I. (2017). Striatal dopaminergic modulation of reinforcement learning predicts reward-oriented behavior in daily life. *Biological Psychology, 127*, 1-9. doi:10.1016/j.biopsycho.2017.04.014

Kasanova, Z., Ceccarini, J., Frank, M. J., van Amelsvoort, T., Booij, J., van Duin, E., . . . Myin-Germeys, I. (2018a). Intact striatal dopaminergic modulation of reward learning and daily-life reward-oriented behavior in first-degree relatives of individuals with psychotic disorder. *Psychological Medicine, 48*(11), 1909-1914. doi:10.1017/S0033291717003476

Kasanova, Z., Oorschot, M., & Myin-Germeys, I. (2018b). Social anhedonia and asociality in psychosis revisited. An experience sampling study. *Psychiatry Res, 270*, 375-381. doi:10.1016/j.psychres.2018.09.057

Kendler, K. S., & Myers, J. (2010). The genetic and environmental relationship between major depression and the five-factor model of personality. *Psychological Medicine, 40*(5), 801-806. doi:10.1017/s0033291709991140

Keren, H., O'Callaghan, G., Vidal-Ribas, P., Buzzell, G. A., Brotman, M. A., Leibenluft, E., . . . Stringaris, A. (2018). Reward Processing in Depression: A Conceptual and Meta-Analytic Review Across fMRI and EEG Studies. *Am J Psychiatry, 175*(11), 1111-1120. doi:10.1176/appi.ajp.2018.17101124

Khazanov, G. K., Ruscio, A. M., & Swendsen, J. (2019). The "Brightening" Effect: Reactions to Positive Events in the Daily Lives of Individuals With Major Depressive Disorder and Generalized Anxiety Disorder. *Behavior Therapy, 50*(2), 270-284. doi:10.1016/j.beth.2018.05.008

Kirsch, P., Schienle, A., Stark, R., Sammer, G., Blecker, C., Walter, B., . . . Vaitl, D. (2003). Anticipation of reward in a nonaversive differential conditioning paradigm and the brain reward system:: an event-related fMRI study. *NeuroImage, 20*(2), 1086-1095. doi:https://doi.org/10.1016/S1053-8119(03)00381-1

Kitsantas, A., Gilligan, T. D., & Kamata, A. (2003). College women with eating disorders: Self-regulation, life satisfaction, and positive/negative affect. *The Journal of Psychology, 137*(4), 381-395.

Knekt, P., Raitasalo, R., Heliövaara, M., Lehtinen, V., Pukkala, E., Teppo, L., . . . Aromaa, A. (1996). Elevated lung cancer risk among persons with depressed mood. *American Journal of Epidemiology, 144*(12), 1096-1103.

Knoll, N., Rieckmann, N., & Schwarzer, R. (2005). Coping as a mediator between personality and stress outcomes: a longitudinal study with cataract surgery patients. *European Journal of Personality, 19*(3), 229-247.

Koch, E. D., Tost, H., Braun, U., Gan, G., Giurgiu, M., Reinhard, I., . . . Reichert, M. (2018). Mood Dimensions Show Distinct Within-Subject Associations With Non-exercise Activity in Adolescents: An Ambulatory Assessment Study. *Frontiers in Psychology, 9*(268), 268. doi:10.3389/fpsyg.2018.00268

Kocot, T., & Goodman, L. (2003). The roles of coping and social support in battered women's mental health. *Violence Against Women, 9*(3), 323-346.

Krieger, T., Zimmermann, J., Huffziger, S., Ubl, B., Diener, C., Kuehner, C., & Grosse Holtforth, M. (2014). Measuring depression with a well-being index: further evidence for the validity of the WHO Well-Being Index (WHO-5) as a measure of the severity of depression. *Journal of Affective Disorders, 156*, 240-244. doi:10.1016/j.jad.2013.12.015

Kwapil, T. R., Silvia, P. J., Myin-Germeys, I., Anderson, A. J., Coates, S. A., & Brown, L. H. (2009). The social world of the socially anhedonic: Exploring the daily ecology of asociality. *Journal of Research in Personality, 43*, 103-106.

Laird, A. R., Fox, P. M., Eickhoff, S. B., Turner, J. A., Ray, K. L., McKay, D. R., . . . Fox, P. T. (2011). Behavioral interpretations of intrinsic connectivity networks. *Journal of Cognitive Neuroscience, 23*(12), 4022-4037. doi:10.1162/jocn_a_00077

Lampert, T., Kroll, L. E., Müters, S., & Stolzenberg, H. (2013). Measurement of the socioeconomic status within the German Health Update 2009 (GEDA). *Bundesgesundheitsblatt Gesundheitsforschung Gesundheitsschutz, 56*(1), 131-143. doi:10.1007/s00103-012-1583-3

Laux, L., Glanzmann, P., Schaffner, P., & Spielberger, C. (1981). STAI: Das State-Trait-Angstinventar. *Göttingen: Hogrefe-Verlag*.

Lederbogen, F., Kirsch, P., Haddad, L., Streit, F., Tost, H., Schuch, P., . . . Meyer-Lindenberg, A. (2011). City living and urban upbringing affect neural social stress processing in humans. *Nature, 474*(7352), 498-501. doi:10.1038/nature10190

Leonhardt, A., Könen, T., Dirk, J., & Schmiedek, F. (2016). How differentiated do children experience affect? An investigation of the within-and between-person structure of children's affect. *Psychological Assessment, 28*(5), 575.

Lewis, P. A., Rezaie, R., Brown, R., Roberts, N., & Dunbar, R. I. (2011). Ventromedial prefrontal volume predicts understanding of others and social network size. *NeuroImage, 57*(4), 1624-1629. doi:10.1016/j.neuroimage.2011.05.030

Liao, Y., Shonkoff, E. T., & Dunton, G. F. (2015). The Acute Relationships Between Affect, Physical Feeling States, and Physical Activity in Daily Life: A Review of Current Evidence. *Frontiers in Psychology, 6*(1975), 1975. doi:10.3389/fpsyg.2015.01975

Little, R. J. A., Lewitzky, S., Heeringa, S., Lepkowski, J., & Kessler, R. C. (1997). Assessment of Weighting Methodology for the National Comorbidity Survey. *American Journal of Epidemiology, 146*(5), 439-449. doi:10.1093/oxfordjournals.aje.a009297

Logothetis, N. K. (2008). What we can do and what we cannot do with fMRI. *Nature, 453*(7197), 869-878.

Lyubomirsky, S., King, L., & Diener, E. (2005). The benefits of frequent positive affect: Does happiness lead to success? *Psychological bulletin, 131*(6), 803.

Mackinnon, A., Jorm, A. F., Christensen, H., Korten, A. E., Jacomb, P. A., & Rodgers, B. (1999). A short form of the Positive and Negative Affect Schedule: Evaluation of factorial validity and invariance across demographic variables in a community sample. *Personality and Individual Differences, 27*(3), 405-416.

Margraf, J. (1994). *Diagnostisches Kurz-Interview bei psychischen Störungen (Mini-DIPS)*. Berlin, Heidelberg, New York: Springer.

Margulies, D. S., Kelly, A. M., Uddin, L. Q., Biswal, B. B., Castellanos, F. X., & Milham, M. P. (2007). Mapping the functional connectivity of anterior cingulate cortex. *NeuroImage, 37*(2), 579-588. doi:10.1016/j.neuroimage.2007.05.019

Matthews, G., Jones, D. M., & Chamberlain, A. G. (1990). Refining the measurement of mood: The UWIST Mood Adjective Checklist. *British Journal of Psychology, 81*(1), 17-42. doi:10.1111/j.2044-8295.1990.tb02343.x

Menon, V., & Uddin, L. Q. (2010). Saliency, switching, attention and control: a network model of insula function. *Brain Struct Funct, 214*(5-6), 655-667. doi:10.1007/s00429-010-0262-0

Meyer-Lindenberg, A., & Tost, H. (2012). Neural mechanisms of social risk for psychiatric disorders. *Nat Neurosci, 15*(5), 663-668. doi:10.1038/nn.3083

Mitchell, R. E., Billings, A. G., & Moos, R. H. (1982). Social support and well-being: Implications for prevention programs. *Journal of Primary Prevention, 3*(2), 77-98. doi:10.1007/BF01324668

Moessnang, C., Schafer, A., Bilek, E., Roux, P., Otto, K., Baumeister, S., . . . Tost, H. (2016). Specificity, reliability and sensitivity of social brain responses during spontaneous mentalizing. *Social Cognitive and Affective Neuroscience, 11*(11), 1687-1697. doi:10.1093/scan/nsw098

Moll, J., & de Oliveira-Souza, R. (2007). Moral judgments, emotions and the utilitarian brain. *Trends in Cognitive Sciences, 11*(8), 319-321. doi:10.1016/j.tics.2007.06.001

Montes-Berges, B., & Augusto, J. M. (2007). Exploring the relationship between perceived emotional intelligence, coping, social support and mental health in nursing students. *Journal of Psychiatric and Mental Health Nursing, 14*(2), 163-171.

Moran, E. K., Culbreth, A. J., Kandala, S., & Barch, D. M. (2019). From neuroimaging to daily functioning: A multimethod analysis of reward anticipation in people with

schizophrenia. *Journal of Abnormal Psychology, 128*(7), 723-734. doi:10.1037/abn0000461

Mortensen, P. B., Pedersen, C. B., Westergaard, T., Wohlfahrt, J., Ewald, H., Mors, O., . . . Melbye, M. (1999). Effects of Family History and Place and Season of Birth on the Risk of Schizophrenia. *New England Journal of Medicine, 340*(8), 603-608. doi:10.1056/nejm199902253400803

Myin-Germeys, I., Peeters, F., Havermans, R., Nicolson, N. A., DeVries, M. W., Delespaul, P., & Van Os, J. (2003). Emotional reactivity to daily life stress in psychosis and affective disorder: an experience sampling study. *Acta Psychiatrica Scandinavica, 107*(2), 124-131. doi:10.1034/j.1600-0447.2003.02025.x

Myin-Germeys, I., & van Os, J. (2007). Stress-reactivity in psychosis: evidence for an affective pathway to psychosis. *Clinical Psychology Review, 27*(4), 409-424.

Myin-Germeys, I., van Os, J., Schwartz, J. E., Stone, A. A., & Delespaul, P. A. (2001). Emotional reactivity to daily life stress in psychosis. *Archives of General Psychiatry, 58*(12), 1137-1144. doi:10.1001/archpsyc.58.12.1137

Nakamura, K., Kawashima, R., Ito, K., Sugiura, M., Kato, T., Nakamura, A., . . . Kojima, S. (1999). Activation of the right inferior frontal cortex during assessment of facial emotion. *Journal of Neurophysiology, 82*(3), 1610-1614. doi:10.1152/jn.1999.82.3.1610

Nakaya, M., Oshio, A., & Kaneko, H. (2006). Correlations for Adolescent Resilience Scale with big five personality traits. *Psychological Reports, 98*(3), 927-930. doi:10.2466/pr0.98.3.927-930

Nettle, D., & Bateson, M. (2012). The evolutionary origins of mood and its disorders. *Current Biology, 22*(17), R712-721. doi:10.1016/j.cub.2012.06.020

Nielsen, M. O., Rostrup, E., Wulff, S., Bak, N., Lublin, H., Kapur, S., & Glenthoj, B. (2012). Alterations of the brain reward system in antipsychotic naive schizophrenia patients. *Biological Psychiatry, 71*(10), 898-905. doi:10.1016/j.biopsych.2012.02.007

Nusslock, R., Almeida, J. R., Forbes, E. E., Versace, A., Frank, E., Labarbara, E. J., . . . Phillips, M. L. (2012). Waiting to win: elevated striatal and orbitofrontal cortical activity during reward anticipation in euthymic bipolar disorder adults. *Bipolar Disord, 14*(3), 249-260. doi:10.1111/j.1399-5618.2012.01012.x

Ochsner, K. N., Ludlow, D. H., Knierim, K., Hanelin, J., Ramachandran, T., Glover, G. C., & Mackey, S. C. (2006). Neural correlates of individual differences in pain-related fear and anxiety. *Pain, 120*(1-2), 69-77. doi:10.1016/j.pain.2005.10.014

Ogawa, S., Lee, T. M., Kay, A. R., & Tank, D. W. (1990). Brain magnetic resonance imaging with contrast dependent on blood oxygenation. *Proceedings of the National Academy of Sciences of the United States of America, 87*(24), 9868-9872. doi:10.1073/pnas.87.24.9868

Oorschot, M., Lataster, T., Thewissen, V., Lardinois, M., Wichers, M., van Os, J., . . . Myin-Germeys, I. (2013). Emotional experience in negative symptoms of schizophrenia--no evidence for a generalized hedonic deficit. *Schizophr Bull, 39*(1), 217-225. doi:10.1093/schbul/sbr137

Oshio, A., Taku, K., Hirano, M., & Saeed, G. (2018). Resilience and Big Five personality traits: A meta-analysis. *Personality and Individual Differences, 127*, 54-60.

Park, B.-J., Tsunetsugu, Y., Kasetani, T., Hirano, H., Kagawa, T., Sato, M., & Miyazaki, Y. (2007). Physiological Effects of Shinrin-yoku (Taking in the Atmosphere of the Forest)—Using Salivary Cortisol and Cerebral Activity as

Indicators&mdash. *Journal of Physiological Anthropology, 26*(2), 123-128. doi:10.2114/jpa2.26.123

Peeters, F., Nicolson, N. A., Berkhof, J., Delespaul, P., & deVries, M. (2003). Effects of daily events on mood states in major depressive disorder. *J Abnorm Psychol, 112*(2), 203-211. doi:10.1037/0021-843x.112.2.203

Penninx, B. W., Guralnik, J. M., Pahor, M., Ferrucci, L., Cerhan, J. R., Wallace, R. B., & Havlik, R. J. (1998). Chronically depressed mood and cancer risk in older persons. *Journal of the National Cancer Institute, 90*(24), 1888-1893. doi:10.1093/jnci/90.24.1888

Pizzagalli, D. A., Holmes, A. J., Dillon, D. G., Goetz, E. L., Birk, J. L., Bogdan, R., . . . Fava, M. (2009). Reduced caudate and nucleus accumbens response to rewards in unmedicated individuals with major depressive disorder. *Am J Psychiatry, 166*(6), 702-710. doi:10.1176/appi.ajp.2008.08081201

Plancherel, B., & Bolognini, M. (1995). Coping and mental health in early adolescence. *Journal of Adolescence, 18*(4), 459-474.

Plichta, M. M., Schwarz, A. J., Grimm, O., Morgen, K., Mier, D., Haddad, L., . . . Meyer-Lindenberg, A. (2012). Test-retest reliability of evoked BOLD signals from a cognitive-emotive fMRI test battery. *NeuroImage, 60*(3), 1746-1758. doi:10.1016/j.neuroimage.2012.01.129

Power, J. D., Barnes, K. A., Snyder, A. Z., Schlaggar, B. L., & Petersen, S. E. (2012). Spurious but systematic correlations in functional connectivity MRI networks arise from subject motion. *NeuroImage, 59*(3), 2142-2154. doi:10.1016/j.neuroimage.2011.10.018

Pressman, S. D., & Cohen, S. (2005). Does positive affect influence health? *Psychological bulletin, 131*(6), 925.

Radua, J., Schmidt, A., Borgwardt, S., Heinz, A., Schlagenhauf, F., McGuire, P., & Fusar-Poli, P. (2015). Ventral Striatal Activation During Reward Processing in Psychosis: A Neurofunctional Meta-Analysis. *JAMA Psychiatry, 72*(12), 1243-1251. doi:10.1001/jamapsychiatry.2015.2196

Raine, A., & Benishay, D. (1995). The SPQ-B: A brief screening instrument for schizotypal personality disorder. *J Pers Disord, 9*(4), 346-355.

Rehm, J., & Shield, K. D. (2019). Global Burden of Disease and the Impact of Mental and Addictive Disorders. *Curr Psychiatry Rep, 21*(2), 10. doi:10.1007/s11920-019-0997-0

Reichert, M., Braun, U., Gan, G., Reinhard, I., Giurgiu, M., Ma, R., . . . Meyer-Lindenberg, A. (2020). A neural mechanism for affective well-being: Subgenual cingulate cortex mediates real-life effects of nonexercise activity on energy. *Sci Adv, 6*(45), eaaz8934. doi:10.1126/sciadv.aaz8934

Reichert, M., Tost, H., Reinhard, I., Schlotz, W., Zipf, A., Salize, H. J., . . . Ebner-Priemer, U. W. (2017). Exercise versus Nonexercise Activity: E-diaries Unravel Distinct Effects on Mood. *Med Sci Sports Exerc, 49*(4), 763-773. doi:10.1249/MSS.0000000000001149

Reichert, M., Tost, H., Reinhard, I., Zipf, A., Salize, H. J., Meyer-Lindenberg, A., & Ebner-Priemer, U. W. (2016). Within-Subject Associations between Mood Dimensions and Non-exercise Activity: An Ambulatory Assessment Approach Using Repeated Real-Time and Objective Data. *Front Psychol, 7*, 918. doi:10.3389/fpsyg.2016.00918

Rico-Uribe, L. A., Caballero, F. F., Martin-Maria, N., Cabello, M., Ayuso-Mateos, J. L., & Miret, M. (2018). Association of loneliness with all-cause mortality: A meta-analysis. *PloS One, 13*(1), e0190033. doi:10.1371/journal.pone.0190033

Roberts, B. W., Lejuez, C., Krueger, R. F., Richards, J. M., & Hill, P. L. (2014). What is conscientiousness and how can it be assessed? *Developmental Psychology, 50*(5), 1315-1330. doi:10.1037/a0031109

Roohafza, H. R., Afshar, H., Keshteli, A. H., Mohammadi, N., Feizi, A., Taslimi, M., & Adibi, P. (2014). What's the role of perceived social support and coping styles in depression and anxiety? *Journal of Research in Medical Sciences, 19*(10), 944-949.

Russell, D., Peplau, L. A., & Cutrona, C. E. (1980). The revised UCLA Loneliness Scale: concurrent and discriminant validity evidence. *Journal of Personality and Social Psychology, 39*(3), 472-480. doi:10.1037//0022-3514.39.3.472

Russell, J. A., & Carroll, J. M. (1999). On the bipolarity of positive and negative affect. *Psychological Bulletin, 125*(1), 3-30. doi:10.1037/0033-2909.125.1.3

Rutter, M. (2006). Implications of resilience concepts for scientific understanding. *Annals of the New York Academy of Sciences, 1094*, 1-12. doi:10.1196/annals.1376.002

Sallet, J., Mars, R. B., Noonan, M. P., Andersson, J. L., O'Reilly, J. X., Jbabdi, S., . . . Rushworth, M. F. (2011). Social network size affects neural circuits in macaques. *Science, 334*(6056), 697-700. doi:10.1126/science.1210027

Saslow, L. R., Cohn, M., & Moskowitz, J. T. (2014). Positive affect interventions to reduce stress: Harnessing the benefit while avoiding the Pollyanna.

Satterthwaite, T. D., Kable, J. W., Vandekar, L., Katchmar, N., Bassett, D. S., Baldassano, C. F., . . . Wolf, D. H. (2015). Common and Dissociable Dysfunction of the Reward System in Bipolar and Unipolar Depression. *Neuropsychopharmacology, 40*(9), 2258-2268. doi:10.1038/npp.2015.75

Saxe, R., & Kanwisher, N. (2003). People thinking about thinking people: the role of the temporo-parietal junction in “theory of mind”. *NeuroImage, 19*(4), 1835-1842.

Scheier, M. F., Carver, C. S., & Bridges, M. W. (1994). Distinguishing optimism from neuroticism (and trait anxiety, self-mastery, and self-esteem): a reevaluation of the Life Orientation Test. *Journal of Personality and Social Psychology, 67*(6), 1063-1078. doi:10.1037//0022-3514.67.6.1063

Scheres, A., Milham, M. P., Knutson, B., & Castellanos, F. X. (2007). Ventral striatal hyporesponsiveness during reward anticipation in attention-deficit/hyperactivity disorder. *Biological Psychiatry, 61*(5), 720-724.

Schimmack, U., & Grob, A. (2000). Dimensional models of core affect: a quantitative comparison by means of structural equation modeling. *European Journal of Personality, 14*(4), 325-345.

Schmidt, S. C. E., & Woll, A. (2017). Longitudinal drop-out and weighting against its bias. *BMC Medical Research Methodology, 17*(1), 164. doi:10.1186/s12874-017-0446-x

Schreuders, E., Braams, B. R., Crone, E. A., & Guroglu, B. (2021). Friendship stability in adolescence is associated with ventral striatum responses to vicarious rewards. *Nat Commun, 12*(1), 313. doi:10.1038/s41467-020-20042-1

Schultz, W. (2015). Neuronal Reward and Decision Signals: From Theories to Data. *Physiological Reviews, 95*(3), 853-951. doi:10.1152/physrev.00023.2014

Schulz, P., Schlotz, W., & Becker, P. (2004). Trierer Inventar zum Chronischen Stress (TICS) [Trier Inventory for Chronic Stress (TICS)].

Schwarz, K., Moessnang, C., Schweiger, J. I., Baumeister, S., Plichta, M. M., Brandeis, D., . . . Meyer-Lindenberg, A. (2020). Transdiagnostic Prediction of Affective, Cognitive, and Social Function Through Brain Reward Anticipation in

Schizophrenia, Bipolar Disorder, Major Depression, and Autism Spectrum Diagnoses. *Schizophrenia Bulletin, 46*(3), 592-602. doi:10.1093/schbul/sbz075

Schwarz, N. (2012). Why researchers should think "real-time": A cognitive rationale. In (pp. 22-42).

Schwarzer, R., & Warner, L. M. (2013). Perceived self-efficacy and its relationship to resilience. In *Resilience in children, adolescents, and adults* (pp. 139-150): Springer.

Seeley, W. W., Menon, V., Schatzberg, A. F., Keller, J., Glover, G. H., Kenna, H., . . . Greicius, M. D. (2007). Dissociable intrinsic connectivity networks for salience processing and executive control. *Journal of Neuroscience, 27*(9), 2349-2356. doi:10.1523/JNEUROSCI.5587-06.2007

Segovia, F., Moore, J. L., Linnville, S. E., Hoyt, R. E., & Hain, R. E. (2012). Optimism predicts resilience in repatriated prisoners of war: a 37-year longitudinal study. *Journal of Traumatic Stress, 25*(3), 330-336. doi:10.1002/jts.21691

Selten, J. P., van der Ven, E., Rutten, B. P., & Cantor-Graae, E. (2013). The social defeat hypothesis of schizophrenia: an update. *Schizophrenia Bulletin, 39*(6), 1180-1186. doi:10.1093/schbul/sbt134

Shiffman, S., Stone, A. A., & Hufford, M. R. (2008). Ecological Momentary Assessment. *Annual Review of Clinical Psychology, 4*(1), 1-32. doi:10.1146/annurev.clinpsy.3.022806.091415

Singer, T., Seymour, B., O'Doherty, J., Kaube, H., Dolan, R. J., & Frith, C. D. (2004). Empathy for pain involves the affective but not sensory components of pain. *Science, 303*(5661), 1157-1162. doi:10.1126/science.1093535

Sinha, R., Lacadie, C. M., Constable, R. T., & Seo, D. (2016). Dynamic neural activity during stress signals resilient coping. *Proceedings of the National Academy of Sciences of the United States of America, 113*(31), 8837-8842. doi:10.1073/pnas.1600965113

Smith, C., & Carlson, B. E. (1997). Stress, coping, and resilience in children and youth. *Social Service Review, 71*(2), 231-256.

Solhan, M., Trull, T., Jahng, S., & Wood, P. (2009). Clinical Assessment of Affective Instability: Comparing EMA Indices, Questionnaire Reports, and Retrospective Recall. *Psychological Assessment, 21*, 425-436. doi:10.1037/a0016869

Steyer, R., Schwenkmezger, P., Notz, P., & Eid, M. (1997). Der Mehrdimensionale Befindlichkeitsfragebogen MDBF [Multidimensional mood questionnaire]. *Göttingen, Germany: Hogrefe*.

Stone, A. A., & Broderick, J. E. (2007). Real-time data collection for pain: appraisal and current status. *Pain Medicine, 8 Suppl 3*, S85-93. doi:10.1111/j.1526-4637.2007.00372.x

Tang, W., Jbabdi, S., Zhu, Z., Cottaar, M., Grisot, G., Lehman, J. F., . . . Haber, S. N. (2019). A connectional hub in the rostral anterior cingulate cortex links areas of emotion and cognitive control. *Elife, 8*. doi:10.7554/eLife.43761

Tomlin, D., Kayali, M. A., King-Casas, B., Anen, C., Camerer, C. F., Quartz, S. R., & Montague, P. R. (2006). Agent-specific responses in the cingulate cortex during economic exchanges. *Science, 312*(5776), 1047-1050. doi:10.1126/science.1125596

Tost, H., Champagne, F. A., & Meyer-Lindenberg, A. (2015). Environmental influence in the brain, human welfare and mental health. *Nat Neurosci, 18*(10), 1421-1431. doi:10.1038/nn.4108

Tost, H., Kolachana, B., Hakimi, S., Lemaitre, H., Verchinski, B. A., Mattay, V. S., . . . Meyer-Lindenberg, A. (2010). A common allele in the oxytocin receptor gene (OXTR) impacts prosocial temperament and human hypothalamic-limbic

structure and function. *Proceedings of the National Academy of Sciences of the United States of America, 107*(31), 13936-13941. doi:10.1073/pnas.1003296107

Tost, H., Reichert, M., Braun, U., Reinhard, I., Peters, R., Lautenbach, S., . . . Meyer-Lindenberg, A. (2019). Neural correlates of individual differences in affective benefit of real-life urban green space exposure. *Nature Neuroscience, 22*(9), 1389-1393. doi:10.1038/s41593-019-0451-y

Trull, T. J., & Ebner-Priemer, U. (2013). Ambulatory assessment. *Annu Rev Clin Psychol, 9*, 151-176. doi:10.1146/annurev-clinpsy-050212-185510

Trull, T. J., & Ebner-Priemer, U. (2014). The Role of Ambulatory Assessment in Psychological Science. *Curr Dir Psychol Sci, 23*(6), 466-470. doi:10.1177/0963721414550706

Tzourio-Mazoyer, N., Landeau, B., Papathanassiou, D., Crivello, F., Etard, O., Delcroix, N., . . . Joliot, M. (2002). Automated anatomical labeling of activations in SPM using a macroscopic anatomical parcellation of the MNI MRI single-subject brain. *NeuroImage, 15*(1), 273-289. doi:10.1006/nimg.2001.0978

Van Overwalle, F. (2009). Social cognition and the brain: a meta-analysis. *Hum Brain Mapp, 30*(3), 829-858. doi:10.1002/hbm.20547

Van Overwalle, F., & Baetens, K. (2009). Understanding others' actions and goals by mirror and mentalizing systems: a meta-analysis. *Neuroimage, 48*(3), 564-584. doi:10.1016/j.neuroimage.2009.06.009

Victor, C. R., & Yang, K. (2012). The prevalence of loneliness among adults: a case study of the United Kingdom. *Journal of Psychology, 146*(1-2), 85-104. doi:10.1080/00223980.2011.613875

Vogt, B. A. (2005). Pain and emotion interactions in subregions of the cingulate gyrus. *Nature Reviews: Neuroscience, 6*(7), 533-544. doi:10.1038/nrn1704

Vogt, B. A., Finch, D. M., & Olson, C. R. (1992). Functional heterogeneity in cingulate cortex: the anterior executive and posterior evaluative regions. *Cerebral Cortex, 2*(6), 435-443. doi:10.1093/cercor/2.6.435-a

Wahlstrom, D., Collins, P., White, T., & Luciana, M. (2010). Developmental changes in dopamine neurotransmission in adolescence: behavioral implications and issues in assessment. *Brain and Cognition, 72*(1), 146-159. doi:10.1016/j.bandc.2009.10.013

Wahlstrom, D., White, T., & Luciana, M. (2010). Neurobehavioral evidence for changes in dopamine system activity during adolescence. *Neurosci Biobehav Rev, 34*(5), 631-648. doi:10.1016/j.neubiorev.2009.12.007

Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: the PANAS scales. *Journal of Personality and Social Psychology, 54*(6), 1063-1070. doi:10.1037//0022-3514.54.6.1063

Watson, D., & Tellegen, A. (1985). Toward a consensual structure of mood. *Psychological Bulletin, 98*(2), 219-235. doi:10.1037//0033-2909.98.2.219

Whalen, P. J., Bush, G., McNally, R. J., Wilhelm, S., McInerney, S. C., Jenike, M. A., & Rauch, S. L. (1998). The emotional counting Stroop paradigm: a functional magnetic resonance imaging probe of the anterior cingulate affective division. *Biological Psychiatry, 44*(12), 1219-1228. doi:10.1016/s0006-3223(98)00251-0

White, M. P., Alcock, I., Grellier, J., Wheeler, B. W., Hartig, T., Warber, S. L., . . . Fleming, L. E. (2019). Spending at least 120 minutes a week in nature is associated with good health and wellbeing. *Scientific Reports, 9*(1), 7730. doi:10.1038/s41598-019-44097-3

White, M. P., Alcock, I., Wheeler, B. W., & Depledge, M. H. (2013). Would you be happier living in a greener urban area? A fixed-effects analysis of panel data. *Psychological Science, 24*(6), 920-928. doi:10.1177/0956797612464659

WHO. (2005). Promoting mental health: concepts, emerging evidence, practice: a report of the World Health Organization, Department of Mental Health and Substance Abuse in collaboration with the Victorian Health Promotion Foundation and the University of Melbourne.

Wichers, M., Geschwind, N., Jacobs, N., Kenis, G., Peeters, F., Derom, C., . . . van Os, J. (2009). Transition from stress sensitivity to a depressive state: longitudinal twin study. *British Journal of Psychiatry, 195*(6), 498-503. doi:10.1192/bjp.bp.108.056853

Wichers, M., Myin-Germeys, I., Jacobs, N., Peeters, F., Kenis, G., Derom, C., . . . Van Os, J. (2007). Genetic risk of depression and stress-induced negative affect in daily life. *British Journal of Psychiatry, 191*, 218-223. doi:10.1192/bjp.bp.106.032201

Wichers, M., Peeters, F., Geschwind, N., Jacobs, N., Simons, C. J., Derom, C., . . . van Os, J. (2010). Unveiling patterns of affective responses in daily life may improve outcome prediction in depression: a momentary assessment study. *Journal of Affective Disorders, 124*(1-2), 191-195. doi:10.1016/j.jad.2009.11.010

Wichers, M., Peeters, F., Rutten, B. P., Jacobs, N., Derom, C., Thiery, E., . . . van Os, J. (2012). A time-lagged momentary assessment study on daily life physical activity and affect. *Health Psychology, 31*(2), 135-144. doi:10.1037/a0025688

Wilhelm, P. (2001). A multilevel approach to analyze ambulatory assessment data: An examination of family members' emotional states in daily life.

Wilhelm, P., & Schoebi, D. (2007). Assessing mood in daily life: Structural validity, sensitivity to change, and reliability of a short-scale to measure three basic dimensions of mood. *European Journal of Psychological Assessment, 23*(4), 258.

Yucel, M., Wood, S. J., Fornito, A., Riffkin, J., Velakoulis, D., & Pantelis, C. (2003). Anterior cingulate dysfunction: implications for psychiatric disorders? *Journal of Psychiatry and Neuroscience, 28*(5), 350-354.

Zhang, W. N., Chang, S. H., Guo, L. Y., Zhang, K. L., & Wang, J. (2013). The neural correlates of reward-related processing in major depressive disorder: a meta-analysis of functional magnetic resonance imaging studies. *Journal of Affective Disorders, 151*(2), 531-539. doi:10.1016/j.jad.2013.06.039

Zink, C. F., Stein, J. L., Kempf, L., Hakimi, S., & Meyer-Lindenberg, A. (2010). Vasopressin modulates medial prefrontal cortex-amygdala circuitry during emotion processing in humans. *Journal of Neuroscience, 30*(20), 7017-7022. doi:10.1523/JNEUROSCI.4899-09.2010

Zink, C. F., Tong, Y., Chen, Q., Bassett, D. S., Stein, J. L., & Meyer-Lindenberg, A. (2008). Know your place: neural processing of social hierarchy in humans. *Neuron, 58*(2), 273-283. doi:10.1016/j.neuron.2008.01.025

Zonderman, A. B., Costa, P. T., & McCrae, R. R. (1989). Depression as a risk for cancer morbidity and mortality in a nationally representative sample. *JAMA, 262*(9), 1191-1195.

Zorn, J. V., Schur, R. R., Boks, M. P., Kahn, R. S., Joels, M., & Vinkers, C. H. (2017). Cortisol stress reactivity across psychiatric disorders: A systematic review and meta-analysis. *Psychoneuroendocrinology, 77*, 25-36. doi:10.1016/j.psyneuen.2016.11.036

Zorrilla, E. P., Luborsky, L., McKay, J. R., Rosenthal, R., Houldin, A., Tax, A., . . . Schmidt, K. (2001). The relationship of depression and stressors to immunological assays: a meta-analytic review. *Brain, Behavior, and Immunity, 15*(3), 199-226. doi:10.1006/brbi.2000.0597

7 PUBLICATION LIST

Gan, G.*, **Ma, R.***, Reichert, M., Giurgiu M., Ebner-Priemer, U., Meyer-Lindenberg, A.*, Tost, H.* Neural structural correlates of affective benefit from real-life social contact. *JAMA Psychiatry*, doi:10.1001/jamapsychiatry.2021.0560. ***These authors contributed equally.***

Ma, R.*, Gan, G.*, Reichert, M., Giurgiu M., Reinhard, I., Moessnang, C., Schwarz, K., Berhe, O., Braun, U., Ebner-Priemer, U. W., Meyer-Lindenberg, A.*, Tost, H.* Longitudinal association between neural and real-life reward processing and the influence of social environmental risk for psychiatric disorders. *In preparation.* ***These authors contributed equally.***

Reichert, M., Braun, U., Gan, G., Reinhard, I., Giurgiu, M., **Ma, R.**, Zang, Z., Hennig, O., Koch, E. D., Wieland, L., Schweiger, J., Inta, D., Hoell, A., Akdeniz, C., Zipf, A., Ebner-Priemer, U. W., Tost, H., Meyer-Lindenberg, A. (2020). A neural mechanism for affective well-being: Subgenual cingulate cortex mediates real-life effects of nonexercise activity on energy. *Science advances*, *6*(45), eaaz8934.

Chen, J., Zang, Z., Braun, U., Schwarz, K., Harneit, A., Kremer, T., **Ma, R.**, Schweiger, J., Moessnang, C., Geiger, L., Cao, H., Degenhardt, F., Noethen, M., Tost, H., Meyer-Lindenberg, A., Schwarz, E. (2020). Association of a reproducible epigenetic risk profile for schizophrenia with brain methylation and function. *JAMA psychiatry*, 77(6), 628-636.

Bilek, E., Itz, M. L., Stoessel, G., **Ma, R.**, Berhe, O., Clement, L., Zang, Z., Robnik, L., Plichta, M. M, Neukel, C., Schmahl, C., Kirsch, P., Meyer-Lindenberg, A., Tost, H. (2019). Deficient amygdala habituation to threatening stimuli in borderline personality disorder relates to adverse childhood experiences. *Biological psychiatry, 86*(12), 930-938.

8 CURRICULUM VITAE

Personal Information

Name: Ren Ma

Date of Birth: 22.12.1991

Place of Birth: Anhui, China

Nationality: Chinese

Father: 马标

Mother: 郭维如

Academic Education

- 09/2016 – present

PhD student, Department of Psychiatry and Psychotherapy, research group Systems Neuroscience in Psychiatry; Central Institute of Mental Health, Medical Faculty Mannheim, University of Heidelberg, Germany

Supervisor: Prof. Dr. Dr. Heike Tost

- 09/2013 ─ 06/2016

Master of Education, Psychology

Medical Psychological Institute of the Second Xiangya Hospital, Central South University, China

- 09/2009 ─ 06/2013

Bachelor of Science, Psychology

Department of Psychology, Wuhan University, China

9 ACKNOWLEDGEMENTS

First of all, I would like to thank Prof. Dr. Dr. Heike Tost for giving me this excellent opportunity to carry out my doctoral research in such a great lab. I appreciate your supervision and support throughout my dissertation project. I also want to thank Dr. Gabriela Gan, my second supervisor, for her invaluable guidance, support, and help for my doctoral study and critical review of the dissertation. I have learned a lot from you, especially regarding good scientific practice and scientific writing.

Further, I would like to thank all of my colleagues from the research group SNiP. I was lucky to be part of such a fantastic team. In particular, Dr. Urs Braun, Dr. Carolin Mößnang, and Dr. Markus Reichert helped supervise my research anytime I need help. Thank Niharika Roychoudhury for the proof reading of this dissertation. Thank all other SNiP members, Dr. Jamila Andoh, Anastasia Benedyk, Oksana Berhe, Dr. Edda Bilek, Marvin Ganz, Lena Geiger-Primo, Anais Harneit, Beate Höchemer, Thomas Kremer, Mirjam Melzer, Alexander Moldavski, Iris Reinhard, Malika Renz, Kristina Schwarz, Janina Schweiger, Xiaolong Zhang, Zhenxiang Zang, Junfang Chen, Han Cao, and Dr. Francesca Zidda. I would also like to thank the graduate program GRK2350 for providing systematic academic training and a supportive peer network.

Finally, I would like to thank my parents, 马标, 郭维如, my brother, 马喆仁, my love of life, Lei 马蕾, and my cute kitten, Dr. paper (糕糕). I couldn't have done my doctoral study without your support and love.

May 25, 2021
Mannheim, Germany