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SUPPLEMENTARY INFORMATION
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Neural correlates of individual differences in affective benefit of real-life urban green space exposure

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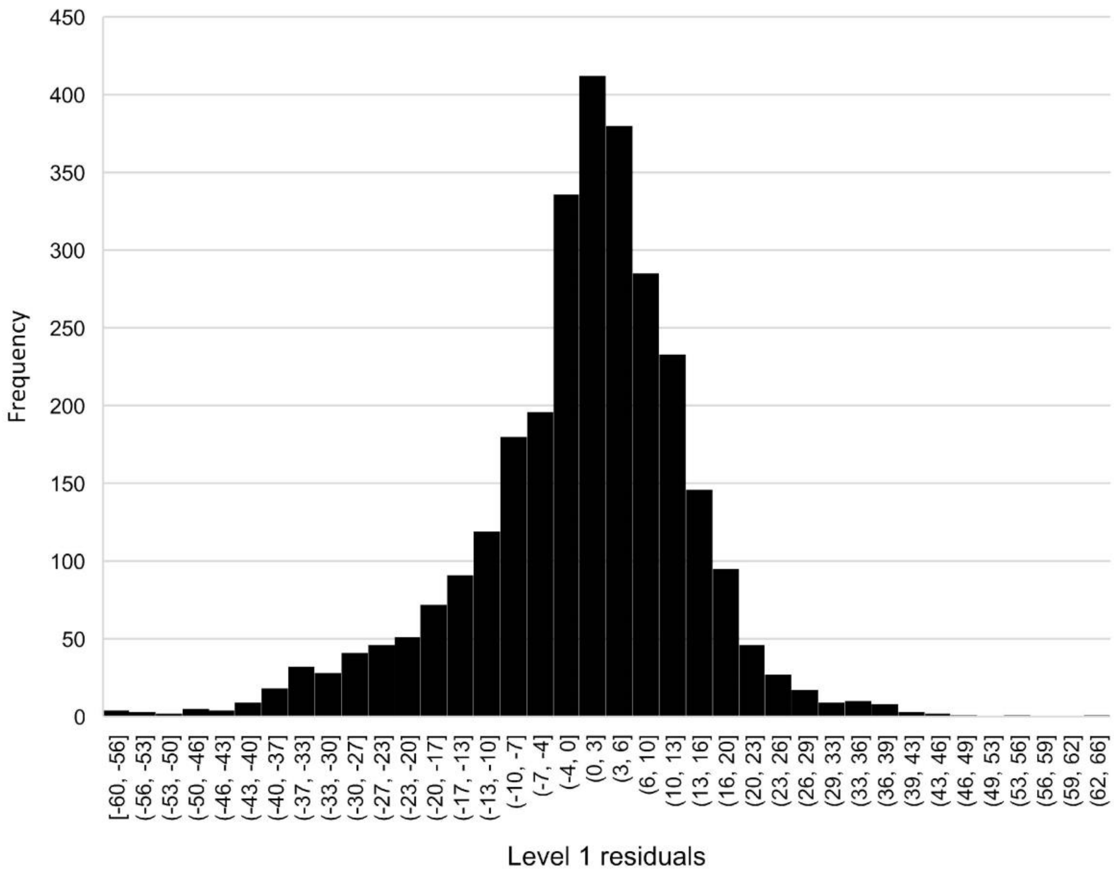
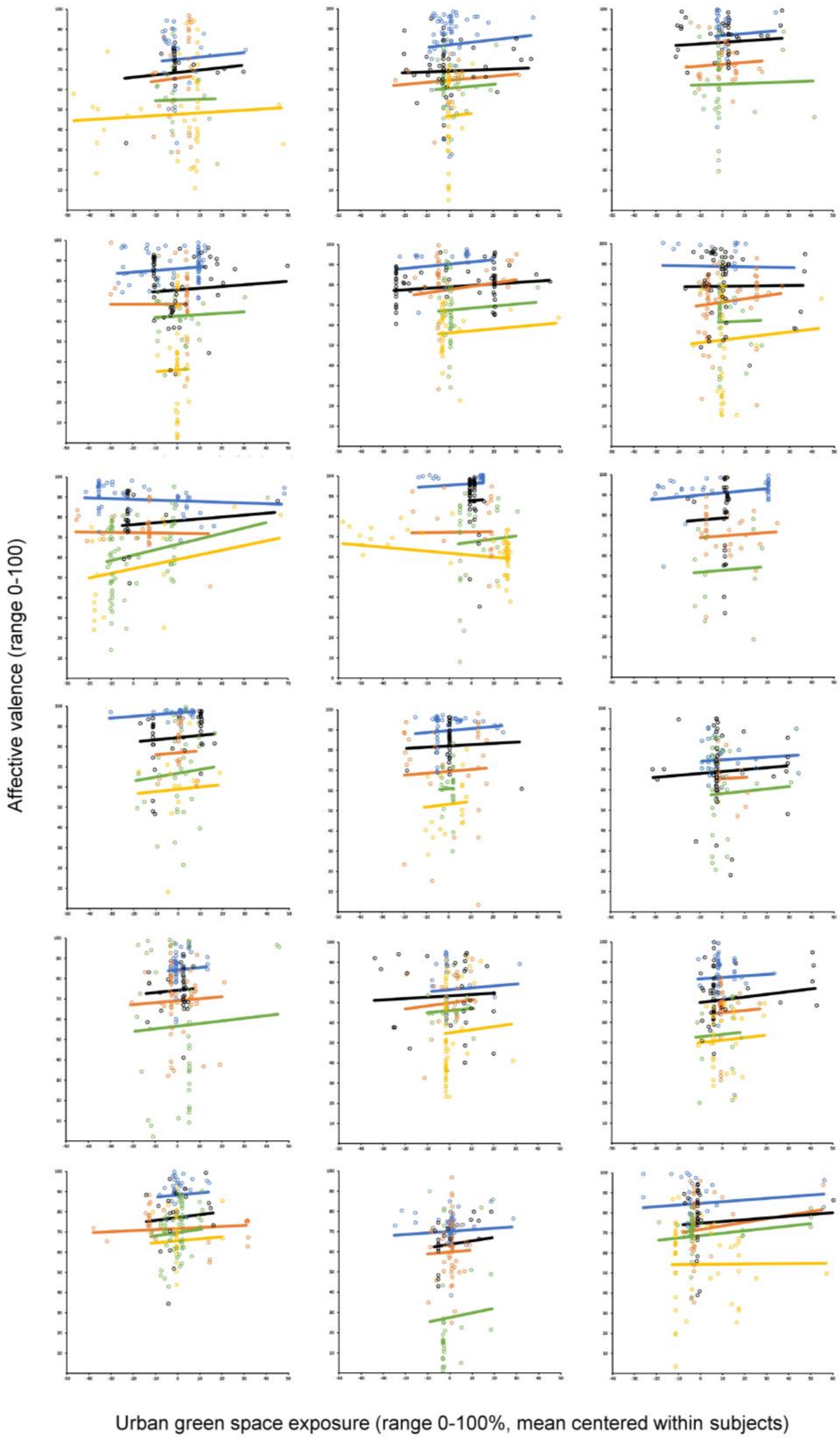


Supplementary Figure 1

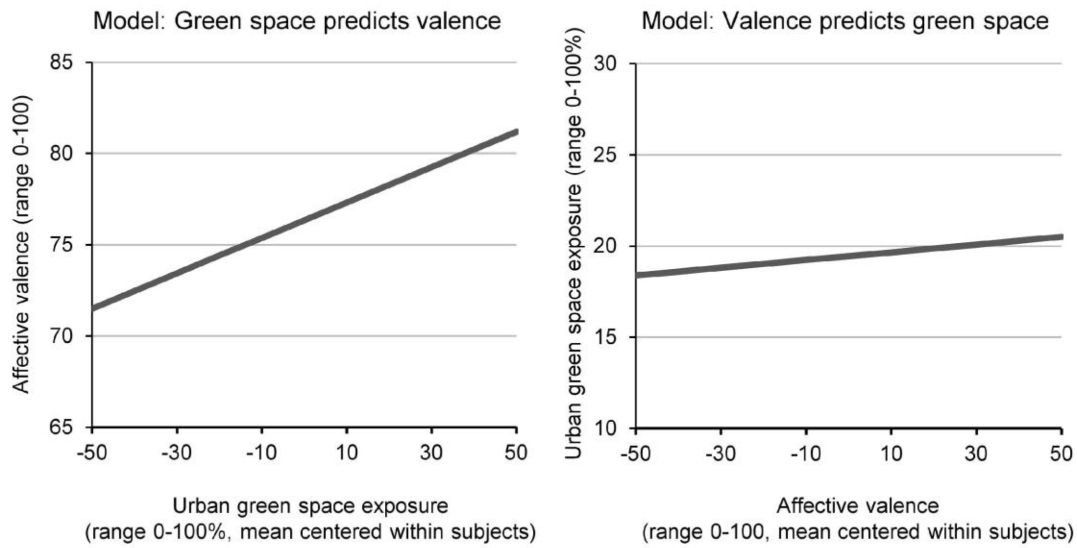
Distribution of level-1 residuals.

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 “multilevel analysis”) in the combined sample (discovery and replication study; n = 85 participants). Graphical inspection confirmed that there was no obvious deviation from normal distribution providing evidence that our multilevel model is suited to deal with the given data structure.



Supplementary Figure 2

Panel plots depicting the raw-data on subject-level including the estimated random slopes from the multilevel model.
Within-subject associations between green space density and affective valence for each individual: The x-axis shows the individual green space exposure centered on the subjects' means (range: 0-100%). The y-axis depicts the individuals' affective valence ratings (range: 0-100). Individual slopes are derived from the random part of the multilevel model (see Methods, section "multilevel analysis") depicting the individuals' within-subject effect of green space on affective valence for each of the participants (discovery and replication study; n = 85 participants). The individuals' raw data points and their random slope estimates are displayed in the same color, respectively. This figure illustrates that although we used a custom-developed sampling strategy (see Methods, section "e-diary sampling strategy"), i.e., a mixed time- and location-based sampling strategy which minimizes the shortcomings of traditional time-based strategies and increases the spatial coverage of assessments and data variability within individuals (Ebner-Priemer, U.W., Koudela, S., Mutz, G. & Kanning, M. Interactive Multimodal Ambulatory Monitoring to Investigate the Association between Physical Activity and Affect. *Front Psychol* **3** (2013); Dorn, H. *et al.* Incorporating land use in a spatiotemporal trigger for ecological momentary assessments. GI_Forum 2015 – Geospatial Minds for Society **1** 113–116 (2015); Törnros, T. *et al.* A comparison of temporal and location-based sampling strategies for global positioning system-triggered electronic diaries. *Geospat Health* **11**, 473 (2016)), the daily routines and main whereabouts (e.g., at home, at work) of participants led to restricted variance in urban green space exposure across the study week. Thus, in a supportive analysis in the combined sample (discovery and replication study; n = 85 participants), we rank ordered the predictor green space exposure within participants and computed an additional multilevel model with exactly the same specifications as in our main model (see Methods, section "multilevel analysis"), but entered the rank ordered green space predictor into the analysis. Here we received only a marginally different effect of urban green space on valence (original green distribution: $P = 0.0026$; rank ordered green distribution: $P = 0.0034$; Supplementary Tab. 8), which further confirmed the robustness of our findings.



Supplementary Figure 3

Causal relation between green space exposure and affect.

Within-subject associations between green space exposure estimates and affective valence for two models with different causal assumptions: (1) green space exposure within the 5 minute time frame prior to the e-diary prompts predicting the following affective valence ratings (i.e., model of our main analysis, standardized beta = 0.056, P = 0.003, left panel) vs. (2) affective valence ratings predicting the green space exposure within the 5 minute time frame following the e-diary prompts (i.e., model with inverted causal logic, standardized beta = 0.017, P = 0.209, right panel). In model (2), all other elements of the model were kept constant with that of our main analysis (see Methods, section “multilevel analysis”). P-values for the beta coefficient are two-sided and derived from the t-statistics of the multilevel model. Dark gray lines illustrate the respective main effect for the estimated green space – affective valence associations. Thus, our data depicted in Figure 3 above support our hypothesis of a causal effect of urban green space exposure on affective valence in everyday life.

Supplementary Tables

Supplementary Table 1: Participant characteristics, Ambulatory Assessment and neuroimaging parameters

	a) Discovery study (n = 33)		b) Replication study (n = 52)	
Demographic variables		n[a]		n
Age (years, mean ± SD[b])	23.64 ± 2.42	33	23.38 ± 2.14	52
Gender (females/males)	21/12	33	28/24	52
Education (years, mean ± SD)	14 ± 1.98	33	13.81 ± 1.77	52
Nationality (German/other)	31/2	33	49/3	52
Body mass index (kg/m^2, mean ± SD)	23.69 ± 6.71	33	23.7 ± 3.84	52
Smoking (smoker/non-smoker)	9/24	33	8/44	52
Household size (individuals, mean ± SD)	2.17 ± 1.18	33	2.48 ± 1.13	52
Household income (€/month after taxes, mean ± SD)[c]	2019.74 ± 1869.79	31	2048.49 ± 1886.87	46
Handedness (right/left/both)	-	-	43/8/1	52
Psychological variables		n		n
Socioeconomic status (SES[1], mean ± SD)	13.57 ± 3.26	33	13.67 ± 3.73	52
Neuroticism (NEO-FFI-30-N[2], mean ± SD)	1.39 ± 0.73	33	1.19 ± .65	52
Trait anxiety (STAI-T[3], mean ± SD)	36.64 ± 10.90	33	34.52 ± 7.06	52
Schizotypical traits (SPQ[4], mean ± SD)	4.28 ± 4.08	29	3.48 ± 2.98	52
Well-being (WBI[5], mean ± SD)[d]	62.42 ± 20.78	33	65.15 ± 15.47	52
Life quality (SWLS[6], mean ± SD)	27.55 ± 6.57	33	27.65 ± 4.84	52
Daily stress (ABF[7], mean ± SD)[e]	29.4 ± 29.09	30	29.11 ± 21.59	49
Perceived social status (McArthur scale[8], mean ± SD)	5.97 ± 1.67	33	6.38 ±1.29	52
Ambulatory Assessment		n		n
E-diary prompts per day	12.36 ± 1.72	33	12.43 ± 1.36	52
Answered e-diary prompts	9.84 ± 2.39	33	9.38 ± 2.38	52
Total affective valence assessments	2272	33	3415	52
Reduced affective valence assessments[f]	1134	33	1779	52
Total affective valence assessments per person	34.36 ± 13.31	33	34.21 ± 13.45	52
Intra-class correlation coefficient: valence[g]	0.379	33	0.484	52
Intra-class correlation coefficient: green exposure[h]	0.493	33	0.544	52
fMRI task performance		n		n
Face matching (% correct, mean ± SD)	-	-	98.96 ± 2.72	52
Form matching (% correct, mean ± SD)	-	-	96 ± 4.59	52
fMRI data quality		n		n
Signal to noise ratio (mean ± SD)	-	-	87.80 ± 15.83	52
Sum motion translation (mm, mean ± SD)	-	-	0.29 ± 0.23	52
Sum motion rotation (degree, mean ± SD)	-	-	0.32 ± 0.22	52
Mean frame-wise displacement (mm, mean ± SD)	-	-	0.15 ± 0.07	52

[a] n = number of individuals for which the information for a given sample and variable is available

[b] SD = standard deviation

[c] We assessed monthly household income after taxes in 13 ordinal categories, i.e., 1) less than 500 €, 2) 500 – 749 €, 3) 750 – 999 €, 4) 1000 – 1249 €, 5) 1250 – 1499 €, 6) 1500 – 1749 €, 7) 1750 – 1999 €, 8) 2000 – 2249 €, 9) 2250 – 2499 €, 10) 2500 – 2999€, 11) 3000 – 3999€, 12) 4000 – 4999€, and 13) more than 5000€. For the descriptive comparison of the two samples in this table we assigned category means to individuals, e.g., a value of 624.5 € to a participant reporting a category 2) income.

[d] Range 0 to 100

[e] ABF sum score

[f] After exclusion of affective valence assessments a) outside the city limits of Mannheim (see also Methods, section "location tracking"), b) before sunrise and after sunset (see also Methods, section "analysis including data

points assessed at nighttime hours”), c) during and 60 min after all exercise activities (see also Methods, section “physical activity”), and d) with geolocation information of insufficient quality (see also Methods, section “location tracking”) in the 5 minutes prior to the affective valence assessments

[g] We used intra class correlation coefficients (ICC) to calculate variance estimates of our main predictor and outcome variables: In the discovery study 62.1% of the variance in affective valence can be attributed to within-subject variation, 51.6% of the variance in the replication study respectively.

[h] We used intra class correlation coefficients (ICC) to calculate variance estimates of our main predictor and outcome variables: In the discovery study 50.7% and of the variance in green space exposure can be attributed to within-subject variation, 45.6% of the variance in the replication study respectively.

Supplementary Table 2: Multilevel analysis[a] result of the discovery study (n = 33 participants)

Outcome: affective valence [range 0-100], fixed effects

Predictor	Beta coefficient (BC)	Standardized BC	Standard Error	*T* value (df)	*P* value[b]
Intercept	95.463	-	17.873	5.35 (28.8)	< 0.0001
Main predictor (level 1: within-subject)					
Urban green exposure [%*10^{-2}]	8.706	0.050	3.879	2.24 (1083)	0.025
Covariates of no interest (level 1: within-subject)					
Time [hours]	1.758	0.307	0.574	3.06 (1100)	0.002
Time-squared [hours^2]	-0.128	-0.289	0.044	-2.95 (1099)	0.003
Non-exercise activity [milli-g]	0.006	0.027	0.005	1.15 (1081)	0.251
Situational context					
- Other	-2.220	-	1.159	-1.91 (1095)	0.056
- Work	-4.977	-	1.440	-3.46 (1108)	0.001
- Leisure	0	-	-	-	-
Social contact					
- Alone	-3.331	-	1.014	-3.28 (1104)	0.001
- In company	0	-	-	-	-
Air pressure [hPa]	0.230	0.066	0.180	1.28 (31.1)	0.211
Temperature [°C]	0.152	0.025	0.167	0.91 (1077)	0.362
Covariates of no interest (level 2: between-subject)					
Age [years]	-0.649	-	0.732	-0.89 (28.7)	0.383
Gender: female	6.902	-	3.670	1.88 (28.8)	0.070
Neuroticism	-11.679	-	2.445	-4.78 (28.5)	< 0.0001

Outcome: affective valence [range 0-100], random effects (n = 33 participants)

	Variance estimate	Standard Error	Wald-*Z*	*P* value
Intercept	91.205	25.912	3.52	< 0.001
Air pressure [hPa]	0.735	0.249	2.95	0.002

[a] We conducted Multilevel Analysis and estimated within-subject effects in a random slope model (e-diary assessments nested within participants; the analysis is detailed in the Methods, section “multilevel analysis”).
[b] P values for the beta coefficient are two-sided and derived from the t-statistics of the multilevel model

Supplementary Table 3: Robustness to covariate combinations. To analyze the robustness of the detected effect of urban green space exposure on affective valence, we computed a series of additional multilevel models (model specifications are detailed in the Methods, section "multilevel analysis") with different combinations of covariates using the combined data set of the discovery and replication study (n = 85 participants) consistent with all supplementary analyses presented in our manuscript. Notably, across all tested combinations (including a model without any covariates), the effect of urban green space exposure on affective valence remained robustly significant, supporting the robustness of the effect of urban green space on affective valence.

Predictor(s) in model	**Beta coefficient (urban green exposure)**	***P* value[a]**
Urban green exposure	8.7540	0.0096
Urban green exposure + Time	8.9698	0.0071
Urban green exposure + Time + Time-squared	9.3156	0.0062
Urban green exposure + Time + Time-squared + Non-exercise activity	9.1678	0.0071
Urban green exposure + Time + Time-squared + Non-exercise activity + Situational context	8.6011	0.0072
Urban green exposure + Time + Time-squared + Non-exercise activity + Situational context + Social contact	8.6938	0.0060
Urban green exposure + Time + Time-squared + Non-exercise activity + Situational context + Social contact + Air Pressure	9.5213	0.0030
Urban green exposure + Time + Time-squared + Non-exercise activity + Situational context + Social contact + Air Pressure + Temperature	9.6930	0.0026
Urban green exposure + Time + Time-squared + Non-exercise activity + Situational context + Social contact + Air Pressure + Temperature + Age	9.6939	0.0026
Urban green exposure + Time + Time-squared + Non-exercise activity + Situational context + Social contact + Air Pressure + Temperature + Age + Gender	9.6929	0.0027
Urban green exposure + Time + Time-squared + Non-exercise activity + Situational context + Social contact + Air Pressure + Temperature + Age + Gender + Neuroticism	9.6932	0.0026

[a] P values for the beta coefficient are two-sided and derived from the t-statistics of the multilevel model

Supplementary Table 4: Predictor-covariate relationship.

a) One multilevel model, outcome: green space in the five minutes prior to each valence rating. We conducted supplementary analyses to explore the relationship between our level 1 predictor of interest (green space exposure) and the defined model covariates. Due to the nested data structure, the reporting of a standard Pearson correlation matrix would be misleading because of the resulting inflation of the degrees of freedom. Thus, we addressed this issue conservatively by calculating an additional multilevel model (model specifications are detailed in the Methods, section "multilevel analysis") using the combined data set of the discovery and replication study (n = 85 participants) with percent of green space for the geographical positions in the five minutes prior each valence rating as outcome variable and entering all covariates as predictors.

b) Ten multilevel models (one for each covariate as predictor), outcome: green space in the five minutes prior to each valence rating. To address potential concerns about multi-collinearity, we computed ten multilevel models (one for each covariate as predictor; model specifications are detailed in the Methods, section "multilevel analysis") with green space in the five minutes prior each valence rating as outcome using the combined data set of the discovery and replication study (n = 85 participants) consistent with all supplementary analyses.

	a) One multilevel model		***b) Ten multilevel models***	
Predictor	**Beta coefficient**	***P* value[a]**	**Beta coefficient**	***P* value[a]**
Time	0.000057	0.9839	-0.00125	0.0512
Time squared	-0.00004	0.8367	-0.00008	0.1213
Non-exercise activity	0.000063	0.0166	0.000044	0.0718
Situational context	-0.00864 (other) 0.002434 (work) Reference: at home	0.1336 (other) 0.7245 (work) Reference: at home	0.005362 (other) 0.000077 (work) Reference: at home	0.2134 (other) 0.9906 (work) Reference: at home
Social contact	0.001722	0.7254	0.005188	0.2757
Air Pressure	0.000536	0.3583	0.000706	0.2155
Temperature	-0.00209	0.0421	-0.00215	0.0195
Age	-0.00661	0.2681	-0.00703	0.2447
Gender	-0.05415	0.0515	-0.05899	0.0285
Neuroticism	-0.01264	0.5297	-0.02475	0.2108

[a] P values for the beta coefficient are two-sided and derived from the t-statistics of the multilevel model

Supplementary Table 5: Robustness to correction method for exercise activity. This Table shows the results of an additional robustness analysis in which exercise activity was added as a covariate of no interest to our multilevel analysis (model specifications are detailed in the Methods, section “multilevel analysis”) in the combined data set of the discovery and replication study (n = 85 participants, consistent with all supplementary analyses). As expected and in line with our prior research[9-12], exercising within the 60 min prior to the e-diary prompt showed significant effects on affective valence (P = 0.0003). Importantly, when adding exercise as a covariate to our multilevel model, the effect of urban green space exposure on affective valence remained stable.

Multilevel model specification	Beta coefficient (urban green exposure)	*P* value[a]
Full model w/o exercise	9.6932	0.0026
Full model with exercise as a covariate	10.8405	0.0013

[a] P values for the beta coefficient are two-sided and derived from the t-statistics of the multilevel model

Supplementary Table 6: Inside vs. outside building position. This table gives the results of a robustness analysis in which we tested whether being inside vs. outside a building impacts the effects of urban green space on affective valence. For this, we computed an additional multilevel model consistent with our main model (see Methods, section “multilevel analysis”) using the combined data set of the discovery and replication study (n = 85 participants), which included a covariate encoding whether subjects were inside or outside at the time of valence ratings (by calculating the distance to the nearest building, with 0 meter corresponding to being inside). The effect of urban green space exposure of affective valence remained stable, with a slightly higher and more significant effect of urban green space exposure on affective valence.

Multilevel model specification	Beta coefficient (urban green exposure)	*P* value[a]
Full model w/o inside vs. outside as a covariate	9.6932	0.0026
Full model with inside vs. outside as a covariate	10.6823	0.0014

[a] P values for the beta coefficient are two-sided and derived from the t-statistics of the multilevel model

Supplementary Table 7: Multilevel model covariance specifications. We explored the consequence of a modification of the covariance structure by computing an additional multilevel model in the combined sample (discovery and replication study; n = 85 participants) with exactly the same specifications as in our main model (see Methods, section “multilevel analysis”), but with an ”unstructured” covariance matrix (which allows the covariance between random intercepts and random slopes to be estimated as three parameters) instead of “variance components”. The results show that the effect is stable and even marginally stronger when using the covariance structure specification “unstructured” but the model fit criteria do not support any firm conclusion on which covariance structure specification does fit the data structure better. Thus, there is no indication that our findings are influenced by our multilevel modelling specification of the covariance structure.

Multilevel model covariance specification	beta coefficient (urban green space exposure)	P value[a]	AIC[b]	BIC[c]
Variance component	9.6932	0.0026	24034.1	24043.8
Unstructured	11.2211	0.0012	24033.7	24050.8

[a] P values for the beta coefficient are two-sided and derived from the t-statistics of the multilevel model
[b] AIC: Akaike Information Criterion
[c] BIC: Schwarz's Bayesian Information Criterion. Both fit indices are based on the calculation of the deviance, adjusting for the number of parameters estimated. The BIC uses additionally the sample size.

Supplementary Table 8: Rank-ordered predictor definition. In a supportive analysis in the combined sample (discovery and replication study; n = 85 participants), we rank ordered the predictor green space exposure within participants and computed an additional multilevel model with exactly the same specifications as in our main model (see Methods, section "multilevel analysis"), but entered the rank ordered green space predictor into the analysis. Here we received only a marginally different effect of urban green space on valence, which further confirmed the robustness of our findings.

Multilevel model specification	P value[a]
predictor green space exposure: not rank ordered	0.0026
predictor green space exposure: rank ordered	0.0034

[a] P values for the beta coefficient are two-sided and derived from the t-statistics of the multilevel model

Supplementary Table 9: Multilevel analysis[a] result of the replication study to estimate individual green-affect slopes (n = 52 participants)

Outcome: affective valence [range 0-100], fixed effects

Predictor	Beta coefficient (BC)	Standardized BC	Standard Error	*T* value (df)	*P* value[b]
Intercept	93.886	-	20.298	4.63 (49.5)	< 0.0001
Main predictor (level 1: within-subject)					
Urban green exposure [%*10^{-2}]	9.597	0.055	4.121	2.33 (39.9)	0.025
Covariates of no interest (level 1: within-subject)					
Time [hours]	1.353	0.235	0.438	3.09 (1727)	0.002
Time-squared [hours^2]	-0.091	-0.198	0.034	-2.67 (1727)	0.008
Non-exercise activity	0.005	0.018	0.004	1.01 (1679)	0.315
Situational context					
- Other	-1.064	-	0.923	-1.15 (1667)	0.249
- Work	-4.916	-	1.113	-4.42 (1209)	< 0.0001
- Leisure	0	-	-	-	-
Social context					
- Alone	-1.631	-	0.759	-2.15 (1724)	0.032
- In company	0	-	-	-	-
Air pressure [hPa]	-0.070	-0.021	0.111	-0.63 (39)	0.529
Temperature [°C]	0.064	0.011	0.125	0.50 (1570)	0.618
Covariates of no interest (level 2: between-subject)					
Age [years]	-0.711	-	0.878	-0.81 (48.8)	0.422
Gender: female	7.04	-	3.771	1.87 (48.2)	0.068
Neuroticism	-9.133	-	3.012	-3.03 (48.1)	0.004

Outcome: affective valence [range 0-100], random effects (n = 52 participants)

Random effects	Variance estimate	Standard Error	Wald-*Z*	*P* value
Intercept	159.90	33.6754	4.69	< 0.0001
Green space [%*10^{-2}]	210.74	122.29	1.72	0.042
Air pressure [hPa]	0.341	6.774	2.72	0.003

[a] We conducted Multilevel Analysis and estimated within-subject effects in a random slope model (e-diary assessments nested within participants; the analysis is detailed in the Methods, section "multilevel analysis").
[b] P values for the beta coefficient are two-sided and derived from the t-statistics of the multilevel model

Supplementary Table 10: Variation of time frame of green space exposure on affect. Within-subject associations between urban green space exposure and affective valence for different cumulative time frames: The presented data are derived from three supportive multilevel models across both samples (discovery and replication study; n = 85 participants). In particular, we gradually extended the time frame for green space estimation from 5 minutes to 10, 15, and 20 minutes prior to each valence rating, respectively, with all other elements of the model kept constant with our main analysis (see Methods, section “multilevel analysis”). As hypothesized, these supportive analyses yielded gradually decreasing effect sizes for the green space – valence associations with increasing cumulative time frames supporting a close temporal coupling of green space exposure and affective valence in daily life.

Time definition for green space quantification (in minutes)	Standardized beta coefficient	*P* value (green space – affective valence association)[a]
5	0.056	0.003
10	0.040	0.015
15	0.029	0.079
20	0.017	0.306

[a] P values for the beta coefficient are two-sided and derived from the t-statistics of the multilevel model

Supplementary Table 11: Multilevel model analysis results for alternative radius definitions. The analysis underlying this Table aimed to explore the sensibility of our initial radius definition for the quantification of urban green space exposure (100 meters) by calculating green space – affective valence associations from the same input data but with alternative radius definitions for urban green space quantification. Specifically, we conducted 11 alternative multilevel models across both samples (discovery and replication study; n = 85 participants) in which we introduced different green space predictors on level 1 that were calculated based on gradually decreasing (75, 50 and 25 meters) or increasing (125, 150, 175, 200, 250, 300, 400 and 500 meters) radius definitions around the measured geolocations of our participants, respectively. All other elements of the models were kept constant with that of our main analyses (see Methods, section "multilevel analysis"). In line with our expectations, the descriptive comparison suggested the strongest green space – affective valence associations for the multilevel models at and around the radius definition approximating that of our main analyses (100 meters) and the calculated median visibility within the Mannheim city limits (103.9 meters; the analysis is detailed in the Methods, section "calculation of the median visibility range within Mannheim city limits"), with a plateau of maximum green space – affective valence associations in the radius range between 100-150 meters). In combination, these results further validate our choice of radius definition and support our idea that the reported beneficial effects for emotional well-being relate to the sight of urban green space.

Radius definition for green space quantification (in meters)	Standardized beta coefficient	*P* value (green space – affective valence association)[a]
25	0.0314	0.0764
50	0.0460	0.0129
75	0.0509	0.0055
100	0.0558	0.0026
125	0.0557	0.0024
150	0.0554	0.0030
175	0.0532	0.0037
200	0.0490	0.0058
250	0.0440	0.0126
300	0.0435	0.0141
400	0.0425	0.0149
500	0.0389	0.0272

[a] P values for the beta coefficient are two-sided and derived from the t-statistics of the multilevel model

Supplementary Table 12: Analysis including data points assessed at nighttime hours. In our main analysis, we restricted the inquiry of green space – affective valence associations to daytime hours (see Methods, section "definition of daytime"), since we hypothesized that the affective benefits of urban green space will likely relate to its sight. To explore this assumption, we conducted a supportive multilevel analysis (model specifications are detailed in the Methods, section "multilevel analysis") across both samples (discovery and replication study, n = 85 participants) consistent with all supplementary analyses in which we included all e-diary assessments, including those assessed before sunrise and after sunset, respectively. All other elements of the model were kept constant with that of our main analysis (see Methods, section "definition of daytime"). Notably, compared to the analysis during daytime hours the analysis with additional nighttime data yielded a smaller standardized beta coefficient for the estimated green space – affective valence association although it included more e-diary assessments (which, in theory, should increase statistical power). This observation is consistent with the proposed relevance of the sight of urban green space for emotional well-being.

Multilevel model specification	data points	standardized beta coefficient (urban green space exposure)
w/o nighttime as a covariate	2913	0.056
with nighttime as a covariate	3830 (+ 31.48%)	0.052

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