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Neural responses to instructed positive couple interaction: An fMRI study on compliment sharing

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Abstract

Love is probably the most fascinating feeling that a person ever experiences. However, little is known about what is happening in the brains of a romantic couple –the central and most salient relationship during adult age – while they are particularly tender and exchanging loving words with one another.

To gain insight into nearly natural couple interaction, we collected data from N = 84 individuals (after including N = 43 heterosexual romantic couples) simultaneously in two functional magnetic resonance imaging scanners, while they sent and received compliments, i.e. short messages about what they liked about each other and their relationship. Activation patterns during compliment sharing in the individuals revealed a broad pattern of activated brain areas known to be involved in empathy and reward processing. Notably, the ventral striatum, including parts of the putamen, was activated particularly when selecting messages for the partner. This indicates that the anticipation of a beloved person's positive reaction is rewarding already. Therefore, we provide initial evidence that the neural systems underlying giving a verbal treat to a romantic partner seem to involve dopaminergic basal ganglia.

These results can have important implications for the neurobiological mechanisms protecting and stabilizing romantic relationships, which build a highly relevant aspect of human life and health.

Significance Statement

Not only is being in a romantic relationship and interacting with a partner linked to subjective joy, it is also to mental and physical health. To investigate central brain mechanisms of couple interaction, we used a realistic positive interaction task in 43 heterosexual couples in two parallel fMRI scanners that tests the neural responses to compliment sharing. Receiving compliments resulted in a broad range of reward-related brain networks and empathy-related networks. Selecting compliments to send to the partner involved the dopamine-rich ventral striatum even stronger, indicating the anticipation of giving a treat to one's partner is rewarding already. These findings suggest that neural reward mechanisms underlying joy during couple interaction are involved in maintaining relationships and promoting health.

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Introduction

In almost all human cultures, romantic love is viewed as a central concept to giving meaning and joy to a person's life. Social identity theory states that individuals derive parts of their identity from belonging to a group, a family, or a romantic relationship (Scheepers and Ellemers, 2019) and such social identification is related to less harmful stress as mediated by social support (Haslam et al., 2005). Specifically being in a functional couple relationship is even linked to better health and longer lives (Braithwaite and Holt-Lunstad, 2017).

The health-related impact of couple relationships is very likely centrally mediated by a combination of neural networks and structures, such as the reward system and the limbic system. An interaction of the neuromodulator oxytocin and the neurotransmitter serotonin in the nucleus accumbens (Dölen et al., 2013) has been shown to mediate social reward. As parts of the dopaminergic reward system, the accumbens, together with putamen and ventral tegmental area (VTA) among others, are involved in the initiation of joyful behaviors and feelings in general, but especially social reinforcements (Izuma et al., 2008; Dölen et al., 2013). Stimulation of dopaminergic reward systems might thus be one underlying mechanism supporting initializing and maintaining couple relationships (Bartels & Zeki, 2004). In previous research, interacting with the partner or observing a partner picture was associated with elevated activation in the VTA, hippocampus, insula (Bartels and Zeki, 2004), anterior cingulate cortex (ACC) (Aron et al., 2005) posterior superior temporal sulcus (pSTS), and anterior temporal lobe (ATP)(Van der Gaag et al., 2007).

One precondition for functional social interaction and for romantic couple relationships in particular is a theory of mind (ToM), the ability to infer the status of knowledge of another person. ToM is related to activation of the superior temporal brain, temporal, and frontal areas (Dodell-Feder et al., 2015), while actual empathy recruits the anterior insula (Kennedy and Adolphs, 2012; Thornton et al., 2019). During empathy-related processes, the accumbens is also interacting with the ACC (Smith et al., 2021). In addition, the mirror neuron system, which comprises parietal and frontolateral brain areas, is involved in social perception and action (Mier et al., 2010).

Furthermore, social integration and the perception of belonging increase positive affect and self-esteem (Ellemers et al., 1999). Positive feedback acts presumably as an indicator of social integration. Imaging studies have shown that receiving compliments from a stranger or from one's own mother involved the dorsal medial prefrontal cortex (DMPFC) (Hooley et al.,

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2005), ACC, and temporal areas (Miedl et al., 2016). Based on this, receiving compliments from the partner can be considered highly relevant to evaluating the social self, the level of integration and affection and, thereby, act in a particularly rewarding and health-beneficial way. To investigate the neural responses to tender partner compliments, we have adapted the previously established standard instructed partnership appreciation task (Pfeifer et al., 2020; Warth et al., 2020) for a functional imaging (fMRI) paradigm. We compared compliments from the partner to "self compliments" (i.e., attributes that the participants defined about themselves), since the mental reflection of positive attributes per se could improve mood (Nicolson et al., 2020) by activating reward-related brain areas (Izuma et al., 2008; Frewen et al., 2020).

For general compliment processing we expected that receiving compliments from the partner would result in elevated activation in a broad network including VTA, hippocampus, insula, ACC, and pSTS, (Van der Gaag et al., 2007). In addition, reward-related task phases as well as phases of reward anticipation (Filimon et al., 2020) should be related to activation in the dopaminergic system: the ventral striatum including the nucleus accumbens. While a participant is actively choosing a compliment, we expected activity known for reading and decision making, and when a participant is sending the compliment, the areas relevant for ToM should be activated, along with mirror neuron areas when they are observing partners' reactions. These activation patterns should become evident using whole brain approaches.

Methods

Participants

Eighty six heterosexual participants (from 43 romantic couples) who were in love and exclusively dating for at least six months were recruited in the Rhine-Neckar metropolitan area, Germany; see Table 1 for sample characteristics. In addition to sociodemographic data, participants provided information on their relationship quality (Partnership Questionnaire, PFB (Hahlweg, 1979), including the scales for tenderness, conflict, and joint interests. Particularly happy couples (reporting at least 5 on a 6-point single-item rating scale on general relationship satisfaction) were included in the study. All participants were eligible for MRI scanning, right-handed, without history of mental disorders and knew sufficient German language to fully understand all instructions. Couples provided written informed consent and were reimbursed 80€ per couple for their participation. The study was conducted in

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accordance with the Declaration of Helsinki and approved by the Ethics Committee of Heidelberg University Medical Faculty (#2011-222N-MA).

Paradigms

In an interview session with the individual participants prior to the MRI session, all participants were handed a list of 23 areas of individual traits and relationship aspects, based on factors of the PFB (e.g., trust, humor, intimacy). Based on these areas, participants were asked to generate up to 18 short positive messages (compliments) about their partner for use in the upcoming experiment. In addition, participants created up to 18 compliments about themselves to be viewed as control stimuli. The compliments were kept confidential until the MRI session. Non-German native speaking couples were allowed to provide compliments in their native language. The paradigm consisted of 15 trials per condition (receiving, sending, self compliment). In the send and receive compliment condition, each trial consisted of two phases, lasting 10s each. In the first phase, the sender chose one of four compliments shown on his/her screen, and the receiver waited for the partner to select the message. In the second phase of the trial, the compliment was revealed to both partners. In the self compliment paradigm, running on both scanners simultaneously, trials consisted of two phases as well: in the first phase, the text ‘Please wait, computer is choosing your compliment’ was displayed to both participants, in the second one, the text appeared: ‘Computer has chosen: compliment_text‘. Both phases of each trial were jittered on average by 775ms, one whole trial lasted 32.5s. All texts were presented on the left-hand side of the screen. On the right-hand side, a live video of the partner taken with a wide-angle camera (MRC Systems GmbH, Heidelberg, Germany) in infrared light was shown continually during all paradigms. The participants were randomly assigned to one of the two scanners. The order of which partner sent first, as well as the assignment of sexes to the scanner and the orders to the scanner were balanced. The temporal order of paradigms (partner vs. self) and the initial sender-sex-scanner matching was randomized and balanced across the sample. However, the first send/receive condition was always followed by the complimentary send/receive condition. The task followed an anatomical measurement and a joint attention paradigm (Bilek et al., 2015).

Data acquisition

Data was acquired with two synchronized 3 Tesla Siemens Tim TRIO scanners, where one scanner was triggered by the other one. Twelve-channel head coils were used. A T2* gradient echo-planar imaging sequence was applied with the following parameters: 28 axial slices,

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with transversal orientation, oriented first to AC/PC line and then flipped by -25°, 4 mm slice thickness, 1 mm gap, field of view 192 mm, voxel size 3x3x4 mm3. Repetition time (TR) was 1.55s with sampling delay of 10ms, and 1.54s. Echo time was 30ms, flip angle 73°. Slices were acquired in descending order, with A/P phase encoding direction. The GRAPPA method with an acceleration factor of 2 was used. A total of 327 (triggering)/ 324 (triggered scanner) scans were collected per condition. The first 7 (triggering)/4 (triggered scanner) scans were discarded during conversion of DICOM-files into 4d niftis by MRIConvert (version. 2.0 rev. 216) to account for saturation effects, resulting in 320 scans available for analysis per condition.

A high-resolution (voxel size 1x1x1mm) T1 anatomical scan was acquired for individual anatomical registration purposes.

Data analyses and preprocessing

fMRI data were analyzed using SPM12 (v771). The anatomical image was segmented and normalized to the SPM12 TPM MNI template. Preprocessing of the functional data involved slice-time correction, realignment to the mean image, and co-registration of the functional images (mean and others) to the anatomical image. The co-registered functional data was normalized to MNI space, resampled to $3mm^3$ voxels, and smoothed with a Gaussian kernel with full-width-at-half-maximum FWHM=8x8x8 mm. Volumes affected by small movement artefacts were identified with the ART toolbox (http://www.nitrc.org/projects/artifact_detect ; parameters: framewise displacement >0.5mm, image intensity change z>4, and exclusion criterion for a measurement: >25% affected volumes).

Of the original 86 fMRI measurements, we had to exclude nine from the activation analysis of the send-paradigm (resulting in N=77) and seven measurements from the activation analysis of the receive-paradigm (resulting in N=79) due to excessive head motion, technical problems, or aborted measurements due to time constraints. In total, this resulted in 14 participants having to be excluded from the comparison of the receive-paradigm with the self compliment-paradigm (N=72).

First, we analyzed the task-related activation in the individuals' brains by means of general linear modeling. A first-level model with three sessions for the three separate conditions of the experiment was set up to allow for both within-session and across-session contrasts. With the conditions, the individual phases (waiting for and receiving a compliment, as well as selecting and observing shared compliments) were modeled as blocks. Signals from

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cerebrospinal fluid and white matter, 24 movement parameters (six standard parameters, their backward derivatives, and their squared versions), and ART dummy regressors were included as nuisance regressors. A high-pass filter with a frequency cutoff of 128s was applied, as well first-degree autoregression.

In the group analyses, age, sex and scanner were included as covariates. Analyses were conducted using one-sample t-tests over the respective contrasts. Contrasts of interests were [Receiving > Waiting] within blocks (partner compliment and self compliment) and [Receiving > Waiting] compared between blocks (partner compliment and self compliment) as well as a contrast between the active block [Choosing compliment > Observing sent compliment] and the passive block [Receiving > Waiting]. All activation results are reported with $p<0.05$ whole-brain FWE-corrected significance. Beta estimates were extracted to visualize the activity of the ventral striatum (anatomical region-of-interest) during conditions.

Results

Activation of individuals when receiving a compliment

When participants were passively receiving compliments (both from the partner and self compliments) as compared to the waiting phases (within blocks), increased activation in a broad network of IFG, DLPFC, VMPFC, midbrain-structures and temporal gyri was observed, see Tables 2 and 3 and Fig. 1a and b.

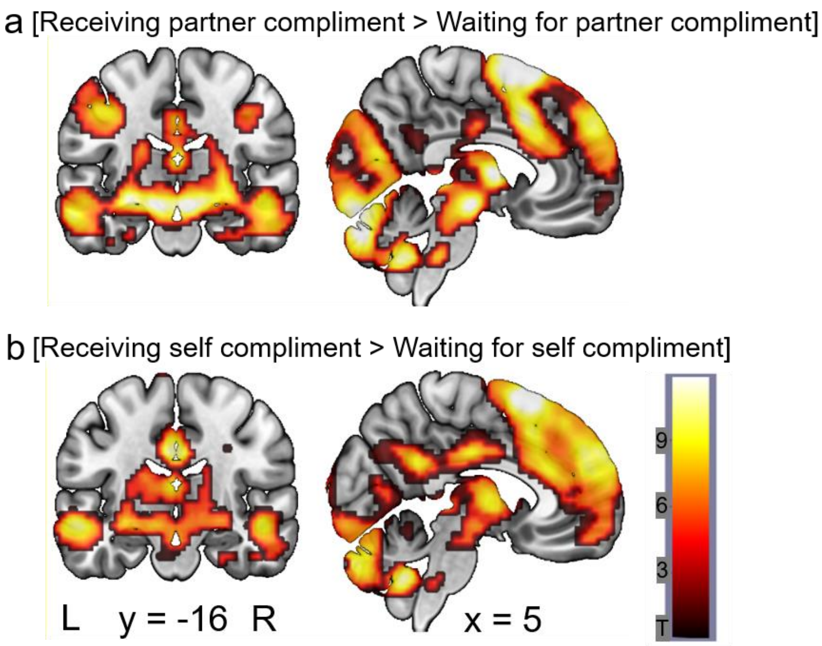

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Fig.1. Higher activation during receiving compliments than during waiting, 1a receiving partner compliments 1b receiving self compliments. All figures p<.05, whole brain FWE corrected (x = 5 y= -16), T-scale applied for both panels.

Activations of individuals when receiving partner vs. self compliments

Contrasting receiving compliments from the partner with self compliments (between the two passive blocks) showed increased VMPFC, ACC, and IFG activity for receiving partner compliments (Table 4, Fig 2a) and higher insula, temporal, and amygdala activity when waiting for partner compliments; i.e. anticipating a compliment (Table 5, Fig 2b).

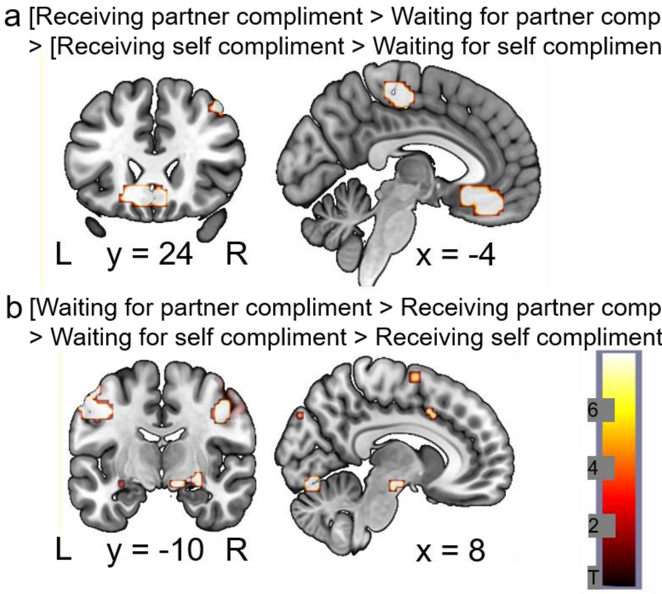

Fig.2. Higher brain activation during partner- than during self compliments, 2a receiving partner compliments (receive partner-compliments (receive > wait) > receive self compliments (receive > wait)) (x =-4, y= 24), 2b waiting for partner compliments (waiting for partner-compliments (wait > receive) > waiting for self compliments (wait > receive)) (x= 8, y=-10)

Activation of individuals when sending compliments

Comparing brain responses during the blocks of actively sending and passively receiving of partner compliments, we found that receiving involves larger TPJ, posterior cingulate, and insula activity (Table 6, Fig 3a) but selecting/sending compliments for the partner involved an even broader limbic and reward network, including putamen, caudate nucleus, globus pallidus, insula, and hippocampus (Table 7, Fig 3b and for beta estimates for the activity of the ventral striatum see Fig 4).

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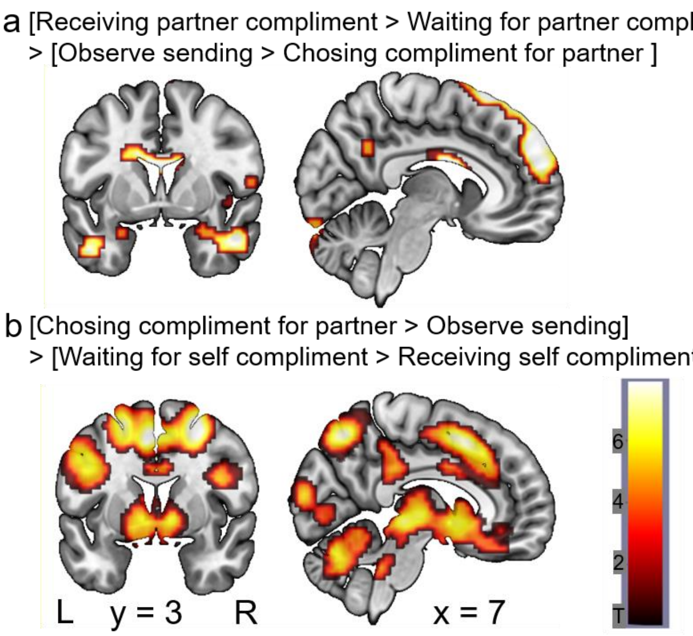

Fig. 3. Activation compared to compliment sending. 3a receiving partner compliment (receive > wait) > sending (choose > observe). 3b sending (choose > observe) > receive partner-compliment (wait >receive), both x 7 = y = 3, t-scale applies to both panels

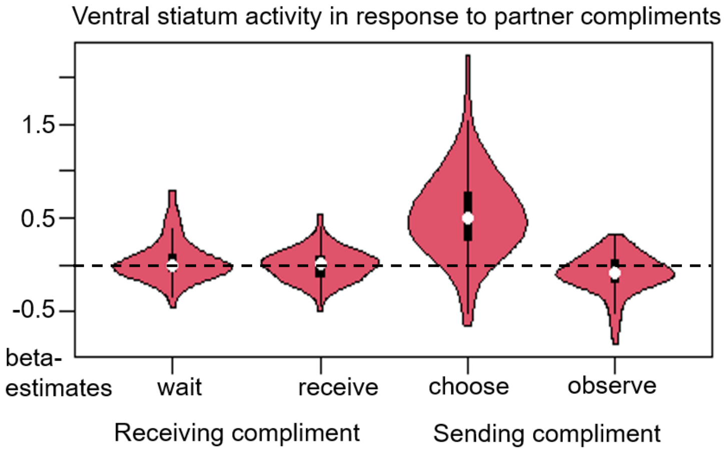

Fig. 4. Beta estimates on ventral striatum activation during the experimental phases of sending and receiving partner compliments; white dots indicate means, black bars indicate SEM.

We found no sex differences in any comparison.

Taken together, these results suggest similar activation patterns for self compliment and partner compliment in the paradigm: elevated activation in DL/VMPFC, precuneus, and temporal gyrus when receiving compliments. DLPFC and posterior cingulate are especially

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sensitive to receiving partner compliments, while temporal lobe and amygdala respond to the anticipation of partner compliments. Interestingly, choosing and sending compliments yielded the strongest activation patterns in the limbic, mentalizing (ToM), and reward systems.

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Discussion

For most adult humans, couple relationships are *the* most relevant social relationship, and interacting with the partner modulates momentary affect and long-term health-related outcomes (Braithwaite and Holt-Lunstad, 2017). Exchanging praise and compliments are one element of positive couple interaction and specific compliments in the relationship are assumed to increase social identity (Ellemers, Kortekaas & Ouwerkerk, 1999). The rationale of the present study was to investigate the neural responses when sending and receiving such compliments, as well as receiving self compliments. In summary, we found that both receiving compliments from the partner and self-generated positive attributes activated the salience and limbic networks, as well as the mirror neuron system, as hypothesized. Differential effects occurred especially during the anticipation of the response to a compliment.

The complex activation pattern to receiving compliments corresponded to the activation seen in previous research investigating the reading of emotionally loaded content (Hsu et al., 2014). Prefrontal and temporal areas, as well as the insula, were involved in both receiving partner compliments and self compliments. This is in line with the notion that the general processing of self-referential information involves the reward circuitry (Frewen et al., 2020) and the dorsal striatum in particular (as part of the nigrostriatal pathway) is involved in comparing predicted and received reward (Oyama et al., 2010).

Amygdaloid responses during the anticipation of partner compliments, relate to the 'emotional' salience network, but also with social reward (Chan et al., 2018). Receiving partner compliments included activation of ACC and temporal gyri. Such activation patterns are part of the "social brain" (Kennedy and Adolphs, 2012) and are involved in successful communication and mentalizing (Van Overwalle and Baetens, 2009; Laurita et al., 2017). Here, they might serve as an indicator of ToM and the sender's mental engagement with choosing a particular compliment.

The compliment choosing phase was associated with complex activation patterns in the senders' brain which included the dopaminergic reward system. The ventral striatum and neural midline structures showed the strongest activation when choosing a compliment as compared to the other conditions (see Fig 4). While this was not hypothesized, these results

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are well in line with previous reports indicating that emotion sharing is rewarding (Wagner et al., 2014), and striatal activation during the anticipation of reward (Filimon et al., 2020). Other examples of rewarding anticipation of prosociality include supporting financially family members, which elicits activation in the mesolimbic dopaminergic system (Telzer et al., 2010), as well as deciding to donate to charities, which recruited the ventral and dorsal striatum and VTA (Moll et al., 2006). Similarly, Harbaugh et al. (2007) found that both mandatory and voluntary contributions to charities recruited the same areas. Finally, Izuma et al. (2010) reported that ventral striatum activity to charitable donations increased in the presence of others, suggesting that this region may be particularly sensitive to social rewards. Our present results add to this line of literature by showing for the first time the differential contributions of dorsal striatum to receiving a treat oneself and of ventral striatum to selecting a treat for someone else during live social interaction.

Our data imply that throughout all conditions, the senders paid close attention to the reaction of their partners during compliment sharing: Activation in oculo-, pre- and motor areas, as well as areas associated with showing emotional, mostly happy, faces such as pSTS and DMPFC suggest involvement of the emotionally ‘extended mirror neuron network’ (Van der Gaag et al., 2007).

In summary, by using a somewhat naturalistic interaction paradigm, the present study design builds on previous research on reward-related brain activation in romantic couples such seeing as pictures from the partner (Acevedo et al., 2012) and extends existing data to a more dynamic couple interaction. To our knowledge, this work is the first to investigate the neural underpinnings of positive emotional interaction between romantic couples using individually meaningful attributes characterizing the relationship and the participants involved, namely self-generated compliments.

The specific areas found to be involved in couple’s compliment sharing are known for social cognition processes, social reward processing, ToM, and facial mimicry (Jabbi and Keysers, 2008; Kennedy and Adolphs, 2012). The involvement of the dopaminergic reward system in particular might serve as an important neurobiological mechanism underlying the ever rewarding aspects of lasting couple relationships. Interestingly, these brain areas are also involved in the action of neuropeptides promoting social behavior, such as oxytocin (Riem et al., 2012; Kreuder et al., 2018). Oxytocin has been shown to interact with the reward system,

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for example when study participants observed the face of their romantic partner (Scheele et al., 2013), and also to influence the appraisal of the relationship (Aguilar-Raab et al., 2019). Furthermore, oxytocin is known to promote health-beneficial effects such as regulation of the stress axes during couple interaction (Ditzen et al., 2009; Zietlow et al., 2018). Therefore, the neural networks reported here and the role of oxytocin might provide a potential neurobiological pathway underlying the association of couple relationships and health.

Our study has some limitations. Investigating heterosexual romantic couples only and having them name, choose, and send the compliments helped create an individualized interaction scenario. However, this allows no extrapolation to unacquainted individuals, platonic friend dyads or same-sex couples. Furthermore, the sample consisted of healthy young couples reporting high relationship satisfaction only. Given inconsistent effects of instructed partnership appreciation in clinical samples (Warth et al., 2020) or couples in therapy (Aguilar-Raab et al., 2018), we cannot extrapolate our findings to marital problems or patient populations (see for instance a study in couple with substance abuse by Flanagan et al., 2018). On the other hand, our findings may still be applicable for some cultures or couple circumstances, since our participants came from Europe and North Africa (15 different nations and 12 mother tongues) therefore generalizability to those parts of the world is given and the individualized compliments have accounted for potential differences. Future studies could systematically investigate cultures and contexts, clinical samples, and couples in the LGBTQIA+ spectrum. We assume similar basic neural effects in all couples though.

In conclusion, our data show substantial involvement of limbic structures and suggest neural reward-related activation during instructed yet individualized couples compliment sharing. The involvement of dopaminergic areas, is evident not only when receiving compliments but is strongest in the ventral striatum when selecting compliments for the partner. This implies some pleasant anticipation on giving a treat to the loved one - which might contribute to the maintenance of lasting relationships beyond the mere receipt of affection and support.

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Table 1

Sample characteristics. Available data presented for participants included for the corresponding fMRI analyses (number of participants in brackets):

	Sending (77), questionnaires (72)				Receiving partner compliment (79), questionnaires (74)				Receiving self compliments (77) questionnaires (72)			
	mean	std	min	max	mean	std	min	max	mean	std	min	max
Age (years)	24.4	2.8	19	32	24.2	3.0	19	32	24.4	3.1	19	32
Education (years)	12.5	1.6	3	15	12.5	1.6	3	15	12.5	1.6	3	15
Relationship duration (years)	3.1	2.8	0.5	12	3.1	2.7	0.5	12	3.1	2.80	0.5	12

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Table 2

Brain responses to (receiving partner compliments > waiting for partner compliments)

peak	**peak**				
p(FWE-corr)	T	x	y	z	Automated anatomical labeling atlas (Tzourio-Mazoyer et al., 2002)
< 0.001	16.79296303	3	14	65	Superior frontal gyrus/Supplementary motor area
< 0.001	12.37275314	-6	5	77	Superior frontal gyrus
< 0.001	11.77529621	6	17	38	Middle cingulate gyrus
< 0.001	15.70023251	-39	-70	-22	Cerebellum
< 0.001	15.21589851	-42	17	-28	Superior temporal gyrus
< 0.001	15.20484543	-45	17	-7	Inferior frontal gyrus
0.0049	5.602838039	66	-40	26	Inferior partietal lobule/Supramarginal gyrus
0.0065	5.522605896	66	-58	11	Superior temporal gyrus
0.0447	4.955034733	-15	-25	-31	Cerebellum

Whole brain analyses; FWE corr, familywise error correction (applies to all tables)

Table 3

Brain responses to (receiving self compliments > waiting for self compliments)

peak	**peak**				
p(FWE-corr)	T	x	y	z	
< 0.001	17.5258503	-42	26	-4	Inferior frontal gyrus
< 0.001	17.06056023	-3	20	59	Superior frontal gyrus/Supplementary motor area
< 0.001	15.37069511	48	26	-1	Inferior frontal gyrus
< 0.001	6.319052696	30	-13	-31	Parahippocampus
0.0042	5.719283581	33	-52	53	Superior parietal gyrus
0.0050	5.673546314	-21	-76	23	Precuneus
0.0054	5.654490948	-3	-52	-16	Vermis/Cerebellum
0.0212	5.255188942	30	-22	35	Postcentral gyrus
0.0353	5.101302147	-9	-16	80	Superior frontal gyrus

Table 4

Brain responses to (receiving partner compliments > waiting for partner compliments) > (receiving self compliments > waiting for self compliments)

peak	**peak**				
p(FWE-corr)	T	x	y	z	
< 0.001	7.01081753	-9	26	-10	Anterior cingulate
< 0.001	6.95619154	-6	35	-22	Rectal gyrus

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< 0.001	6.37565708	-21	41	-13	Middle frontal gyrus
< 0.001	6.97407198	42	50	-4	Middle frontal gyrus
0.0070	5.5989995	24	53	-1	Superior frontal gyrus
0.0002	6.51676655	54	-52	50	Inferior partietal lobule
0.0050	5.69650269	42	-64	53	Angular gyrus
0.0026	5.87921333	3	-28	59	Medial frontal gyrus
0.01062	5.47870684	-9	-31	65	Medial frontal gyrus
0.0064	5.625525	-36	-22	20	Insula
0.0070	5.59888983	36	-19	17	Insula
0.0098	5.50063801	42	23	47	Middle frontal gyrus
0.0122	5.435884	-9	35	-1	Anterior cingulate
0.0189	5.30584526	24	41	-13	Middle frontal gyrus
0.0251	5.21994162	-42	-58	56	Partietal inferior gyrus
0.03185	5.14777374	-54	-55	41	Partietal inferior gyrus

Table 5

Brain responses to (waiting for partner compliments > receiving partner compliments) > (waiting for self compliments > receiving self compliments)

peak	**peak**				
p(FWE-corr)	T	x	y	z	
< 0.001	7.21621704	-30	-64	-22	Cerebellum
< 0.001	6.71068478	-42	-61	-25	Cerebellum
< 0.001	6.43157673	-12	-67	-16	Cerebellum
< 0.001	7.18531132	-48	-13	41	Pre/postcentral gyrus
0.0072	5.59245872	-48	-10	59	Precentral gyrus
< 0.001	6.9873867	42	17	-28	Superior temporal gyrus
0.0012	6.0868845	48	8	-7	Insula
0.0140	5.39685678	36	-1	-25	Amygdala
< 0.001	6.43445444	-39	11	-28	Superior temporal gyrus
0.0011	6.10743856	45	-10	41	Precentral gyrus
0.0014	6.04848385	57	-4	44	Precentral gyrus
0.0017	5.99132061	48	-1	59	Frontal middle gyrus
0.0054	5.67191124	27	-7	-13	Amygdala
0.0073	5.58856153	-6	-88	-10	Calcarine/Lingual gyrus
0.0093	5.51773834	3	2	68	Superior frontal gyrus/Supplementary motor area
0.0100	5.4936924	-15	-1	80	Superior frontal gyrus
0.012	5.44215488	9	-13	-13	Hippocampus
0.0125	5.42972374	-6	-82	17	Cuneus
0.0197	5.29384518	3	-85	38	Precuneus

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0.0242	5.23110056	-30	-13	-13	Hippocampus
0.0357	5.11234665	9	14	38	Middle cingulate
0.0458	5.03419256	-30	-61	-49	Cerebellum
0.0469	5.02685928	15	-19	-13	Hippocampus

Table 6

Brain responses to (receiving partner compliments > waiting for partner compliments) > (observing partner compliments > selecting self compliments)

peak	**peak**				
p(FWE-corr)	T	x	y	z	
< 0.001	16.525074	-36	-13	59	Precentral gyrus
< 0.001	15.8985653	-39	-31	53	Poscentral gyurs
< 0.001	15.8449984	18	-67	56	Superioral parietal gyrus
< 0.001	9.79416847	45	8	26	Inferior frontal gyrus
< 0.001	7.32125902	57	-46	-16	Inferor Temporal gyrus
< 0.001	7.22525072	6	-31	29	Posterior cingulate
< 0.001	6.43974495	-3	-28	29	Posterior cingulate
0.0026	5.8363061	21	-40	-43	Cerebellum
0.0081	5.51446533	-15	-55	-46	Cerebellum
0.0084	5.50423813	-39	-4	14	Insula
0.0190	5.25947666	-48	11	-13	Superior temporal gyrus
0.0263	5.16038084	-30	-58	-34	Cerebellum
0.0304	5.11576033	-54	8	-10	Superior temporal gyrus

Table 7

Brain responses to (choosing self compliments > observing partner compliments) > (waiting for partner compliments > receiving partner compliments)

peak	**peak**				
p(FWE-corr)	T	x	y	z	
< 0.001	12.1697969	21	-91	-34	Cerebellum
< 0.001	6.47661924	3	-88	-19	Cerebellum
< 0.001	11.8543653	-33	-88	-31	Superior/Middle occiptal gyrus
< 0.001	11.2321196	-21	-79	-34	Cerebellum
< 0.001	10.5057125	0	-1	20	Cerebellum
< 0.001	10.3181181	-12	-4	29	Middle cingulate

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< 0.001	8.00352383	-18	-22	29	Nucleus caudatus/Middle cingulate
< 0.001	9.35983181	-54	-67	41	Angular gyrus
< 0.001	8.50362015	-60	-58	29	Supramarginal gyrus
< 0.001	8.44472694	-60	-46	50	Supramarginal gyrus
< 0.001	8.84178734	57	-61	11	Superior temporal gyrus
< 0.001	6.97519064	66	-55	20	Superior temporal gyrus
0.0054	5.63413525	69	-40	29	Supramarginal gyrus
< 0.001	8.6882925	6	56	38	Superior frontal gyrus
< 0.001	8.64810467	6	26	68	Superior frontal gyrus
< 0.001	7.82007265	-6	50	26	Medial Frontal gyrus
< 0.001	7.84036493	-33	-52	2	Lingual gyrus
0.0014	6.01714706	-24	-37	14	Hippocampus
0.0025	5.84849262	-18	-43	14	White matter
< 0.001	7.54454184	27	-7	-7	Globus pallidus/Lentiform nucleus
< 0.001	7.52939987	48	2	-28	Middle temporal gyrus
< 0.001	7.01410103	48	11	-28	Temporal pole
< 0.001	7.29358339	-45	20	53	Middle frontal gyrus
< 0.001	7.24051571	-42	11	-34	Middle frontal gyrus
< 0.001	7.18364382	45	-10	35	Precentral gyrus
< 0.001	6.34821653	33	-46	2	Lingual gyrus
< 0.001	6.16943264	3	-55	32	Middle cingulate/Precuneus
0.0010	6.10089874	-57	-28	-19	Temporal inferior gyrus
0.0023	5.8795042	-63	-19	-19	Temporal middle gyrus
0.0012	6.0625968	0	-28	17	Thalamus
0.0020	5.90837193	57	-1	11	Insula
0.0028	5.81837273	-42	-13	35	Postcentral/Precentral gyrus
0.0042	5.7014122	-36	-13	26	Insula
0.0053	5.63772678	42	5	-4	Insula
0.0069	5.56073284	-27	-1	-22	Amygdala
0.0192	5.25661325	54	-25	-13	Temporal middle
0.0212	5.22633171	57	11	2	Insula
0.0247	5.1791029	51	23	5	Inferior frontal gyrus
0.0339	5.08146048	57	20	-28	Middle temporal pole
0.0399	5.03027153	-33	-7	-19	Parahippocampus
0.04829	4.96986198	-54	-61	-28	Cerebellum

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References

Acevedo BP, Aron A, Fisher HE, Brown LL (2012) Neural correlates of long-term intense romantic love. Social cognitive and affective neuroscience 7:145-159.

Aguilar-Raab C, Eckstein M, Geracitano S, Prevost M, Gold I, Heinrichs M, Bilderbeck A, Ehlert U, Ditzen B (2019) Oxytocin modulates the cognitive appraisal of the own and others close intimate relationships. Frontiers in neuroscience:714.

Aguilar-Raab C, Grevenstein D, Gotthardt L, Jarczok MN, Hunger C, Ditzen B, Schweitzer J (2018) Changing me, changing us: relationship quality and collective efficacy as major outcomes in systemic couple therapy. Family process 57:342-358.

Aron A, Fisher H, Mashek DJ, Strong G, Li H, Brown LL (2005) Reward, motivation, and emotion systems associated with early-stage intense romantic love. Journal of neurophysiology 94:327-337.

Bartels A, Zeki S (2004) The neural correlates of maternal and romantic love. Neuroimage 21:1155-1166.

Bilek E, Ruf M, Schäfer A, Akdeniz C, Calhoun VD, Schmahl C, Demanuele C, Tost H, Kirsch P, Meyer-Lindenberg A (2015) Information flow between interacting human brains: Identification, validation, and relationship to social expertise. Proceedings of the National Academy of Sciences:201421831.

Braithwaite S, Holt-Lunstad J (2017) Romantic relationships and mental health. Current Opinion in Psychology 13:120-125.

Chan Y-C, Hsu W-C, Chou T-L (2018) Dissociation between the processing of humorous and monetary rewards in the 'motivation'and 'hedonic'brains. Scientific reports 8:15425.

Ditzen B, Schaer M, Gabriel B, Bodenmann G, Ehlert U, Heinrichs M (2009) Intranasal oxytocin increases positive communication and reduces cortisol levels during couple conflict. Biological psychiatry 65:728-731.

Dodell-Feder D, Felix S, Yung MG, Hooker CI (2015) Theory-of-mind-related neural activity for one's romantic partner predicts partner well-being. Social Cognitive and Affective Neuroscience 11:593-603.

Dölen G, Darvishzadeh A, Huang KW, Malenka RC (2013) Social reward requires coordinated activity of nucleus accumbens oxytocin and serotonin. Nature 501:179.

Ellemers N, Kortekaas P, Ouwerkerk JW (1999) Self-categorisation, commitment to the group and group self-esteem as related but distinct aspects of social identity. European journal of social psychology 29:371-389.

Filimon F, Nelson JD, Sejnowski TJ, Sereno MI, Cottrell GW (2020) The ventral striatum dissociates information expectation, reward anticipation, and reward receipt. Proceedings of the National Academy of Sciences 117:15200-15208.

Flanagan JC, Fischer MS, Nietert PJ, Back SE, Maria MM-S, Snead A, Brady KT (2018) Effects of oxytocin on cortisol reactivity and conflict resolution behaviors among couples with substance misuse. Psychiatry Research 260:346-352.

Frewen P, Schroeter ML, Riva G, Cipresso P, Fairfield B, Padulo C, Kemp AH, Palaniyappan L, Owolabi M, Kusi-Mensah K, Polyakova M, Fehertoi N, D'Andrea W, Lowe L, Northoff G (2020) Neuroimaging the consciousness of self: Review, and conceptual-methodological framework. Neuroscience & Biobehavioral Reviews 112:164-212.

Hahlweg K (1979) Konstruktion und Validierung des Partnerschaftsfragebogens PFB. Zeitschrift für klinische Psychologie 8:17-40.

Harbaugh WT, Mayr U, Burghart DR (2007) Neural responses to taxation and voluntary giving reveal motives for charitable donations. Science 316:1622-1625.

Haslam SA, O'Brien A, Jetten J, Vormedal K, Penna S (2005) Taking the strain: Social identity, social support, and the experience of stress. British journal of social psychology 44:355-370.

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Hooley JM, Gruber SA, Scott LA, Hiller JB, Yurgelun-Todd DA (2005) Activation in dorsolateral prefrontal cortex in response to maternal criticism and praise in recovered depressed and healthy control participants. Biological psychiatry 57:809-812.

Hsu C-T, Conrad M, Jacobs AM (2014) Fiction feelings in Harry Potter: haemodynamic response in the mid-cingulate cortex correlates with immersive reading experience. Neuroreport 25:1356-1361.

Izuma K, Saito DN, Sadato N (2008) Processing of social and monetary rewards in the human striatum. Neuron 58:284-294.

Izuma K, Saito DN, Sadato N (2010) Processing of the incentive for social approval in the ventral striatum during charitable donation. Journal of cognitive neuroscience 22:621-631.

Jabbi M, Keysers C (2008) Inferior frontal gyrus activity triggers anterior insula response to emotional facial expressions. Emotion 8:775.

Kennedy DP, Adolphs R (2012) The social brain in psychiatric and neurological disorders. Trends in cognitive sciences 16:559-572.

Kreuder AK, Wassermann L, Wollseifer M, Ditzen B, Eckstein M, Stoffel-Wagner B, Hennig J, Hurlemann R, Scheele D (2018) Oxytocin enhances the pain-relieving effects of social support in romantic couples. Human brain mapping.

Laurita AC, Hazan C, Spreng RN (2017) Dissociable patterns of brain activity for mentalizing about known others: a role for attachment. Social Cognitive and Affective Neuroscience 12:1072-1082.

Miedl SF, Blechert J, Klackl J, Wiggert N, Reichenberger J, Derntl B, Wilhelm FH (2016) Criticism hurts everybody, praise only some: Common and specific neural responses to approving and disapproving social-evaluative videos. NeuroImage 132:138-147.

Mier D, Lis S, Neuthe K, Sauer C, Esslinger C, Gallhofer B, Kirsch P (2010) The involvement of emotion recognition in affective theory of mind. Psychophysiology 47:1028-1039.

Moll J, Krueger F, Zahn R, Pardini M, de Oliveira-Souza R, Grafman J (2006) Human fronto–mesolimbic networks guide decisions about charitable donation. Proceedings of the National Academy of Sciences 103:15623-15628.

Nicolson NA, Peters ML, in den Bosch - Meevissen YMC (2020) Imagining a positive future reduces cortisol response to awakening and reactivity to acute stress. Psychoneuroendocrinology 116:104677.

Oyama K, Hernádi I, Iijima T, Tsutsui K-I (2010) Reward prediction error coding in dorsal striatal neurons. Journal of neuroscience 30:11447-11457.

Pfeifer A-C, Schroeder-Pfeifer P, Schneider E, Schick M, Heinrichs M, Bodenmann G, Ehlert U, Herpertz SC, Läuchli S, Eckstein M (2020) Oxytocin and positive couple interaction affect the perception of wound pain in everyday life. Molecular Pain 16:1744806920918692.

Riem MM, Van Ijzendoorn MH, Tops M, Boksem MA, Rombouts SA, Bakermans-Kranenburg MJ (2012) No laughing matter: intranasal oxytocin administration changes functional brain connectivity during exposure to infant laughter. Neuropsychopharmacology 37:1257.

Scheele D, Wille A, Kendrick KM, Stoffel-Wagner B, Becker B, Güntürkün O, Maier W, Hurlemann R (2013) Oxytocin enhances brain reward system responses in men viewing the face of their female partner. Proceedings of the National Academy of Sciences 110:20308-20313.

Scheepers D, Ellemers N (2019) Social identity theory. In: Social psychology in action, pp 129-143: Springer.

Smith ML, Asada N, Malenka RC (2021) Anterior cingulate inputs to nucleus accumbens control the social transfer of pain and analgesia. Science 371:153-159.

Telzer EH, Masten CL, Berkman ET, Lieberman MD, Fuligni AJ (2010) Gaining while giving: An fMRI study of the rewards of family assistance among White and Latino youth. Social Neuroscience 5:508-518.

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Thornton MA, Weaverdyck ME, Mildner JN, Tamir DI (2019) People represent their own mental states more distinctly than those of others. Nature Communications 10:2117.
Tzourio-Mazoyer N, Landeau B, Papathanassiou D, Crivello F, Etard O, Delcroix N, Mazoyer B, Joliot M (2002) Automated anatomical labeling of activations in SPM using a macroscopic anatomical parcellation of the MNI MRI single-subject brain. Neuroimage 15:273-289.
Van der Gaag C, Minderaa RB, Keysers C (2007) Facial expressions: what the mirror neuron system can and cannot tell us. Social neuroscience 2:179-222.
Van Overwalle F, Baetens K (2009) Understanding others' actions and goals by mirror and mentalizing systems: A meta-analysis. NeuroImage 48:564-584.
Wagner U, Galli L, Schott BH, Wold A, van der Schalk J, Manstead AS, Scherer K, Walter H (2014) Beautiful friendship: social sharing of emotions improves subjective feelings and activates the neural reward circuitry. Social cognitive and affective neuroscience 10:801-808.
Warth M, Stoffel M, Winter F, Jarczok MN, Aguilar-Raab C, Ditzen B (2020) Instructed Partnership Appreciation in Depression: Effects on Mood, Momentary Relationship Satisfaction, and Psychobiological Arousal. Frontiers in psychiatry 11:701.
Zietlow A-L, Eckstein M, Nonnenmacher N, Reck C, Schaer M, Bodenmann G, Heinrichs M, Ditzen B (2018) Dyadic coping and its underlying neuroendocrine mechanisms–implications for stress regulation. Frontiers in psychology 9:2600.

AUTHORS' CONTRIBUTION STATEMENT:

B.D., P.K., G.S. E.B and M.E. designed the study; G.S. and M.E. lead the study; G.S., E.B. and M.E. collected the data; M.F.G. and E.B. established the experimental set-up; G.S. and M.F.G ran the reported analyses, M.E., and B.D. wrote the manuscript; All authors provided comments on the manuscript.

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The authors declare that they have no competing interests.

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