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# Personal space regulation by the human amygdala

Daniel P Kennedy<sup>1</sup>, Jan Gläscher<sup>1</sup>, J Michael Tyszka<sup>2</sup> & Ralph Adolphs<sup>1,2</sup>

**The amygdala plays key roles in emotion and social cognition, but how this translates to face-to-face interactions involving real people remains unknown. We found that an individual with complete amygdala lesions lacked any sense of personal space. Furthermore, healthy individuals showed amygdala activation upon close personal proximity. The amygdala may be required to trigger the strong emotional reactions normally following personal space violations, thus regulating interpersonal distance in humans.**

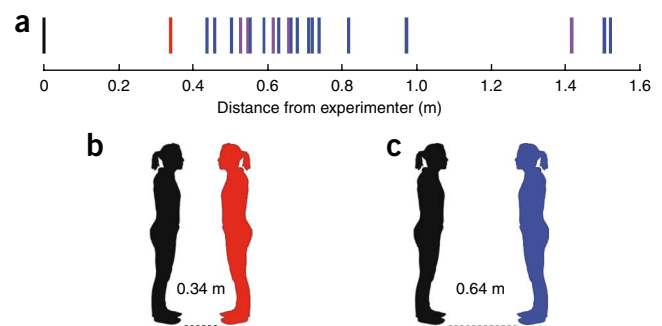
People automatically and reliably regulate the distance maintained between themselves and others during social interaction<sup>1</sup>. Personal space, defined as the area individuals maintain around themselves into which intrusion by others causes discomfort<sup>2</sup>, is one mechanism by which this automatic regulation of interpersonal distance is achieved. However, little is known regarding the neural substrates of personal space. One candidate brain region is the amygdala, as studies in non-human primates have found that this structure is involved in social approach and avoidance<sup>3–5</sup>. Here we show that one's sense of personal space is dependent on the amygdala.

We studied S.M., a 42-year-old woman with complete bilateral amygdalar damage we have described extensively<sup>6,7</sup>. S.M. indicated the position at which she felt most comfortable as a female experimenter approached her from 4.7 m across the room; chin-to-chin distance was recorded using a digital laser measurer. We repeated this procedure four times (counterbalanced with other trial types; see **Supplementary Text**). S.M.'s preferred distance ( $0.34 \pm 0.02$  m; mean and s.d.) was smaller than the smallest preferred distance on any trial of any comparison subject ( $0.76 \pm 0.34$  m, range = 0.44–1.52 m,  $N = 20$ ; **Fig. 1**) and statistically significantly smaller than that of the comparison group (after excluding the three outliers with the largest distance preferences, a mean comparison-subject distance of  $0.64 \pm 0.13$  m,  $Z = -2.20$ ,  $P = 0.014$ , one-tailed; with a modified  $t$ -test,  $t_{16} = -2.14$ ,  $P = 0.024$ .) This highly abnormal pattern was found reliably across various experimental manipulations (gaze direct or averted; subject being approached or approaching; starting close or far; a total of 32 trials per subject;  $Z = -2.38$ ,  $P = 0.009$ , one-tailed;  $t_{16} = -2.31$ ,  $P = 0.017$ , one-tailed, excluding three outliers) and when S.M.'s distance preferences were compared to female controls alone ( $Z = -1.93$ ,  $P = 0.027$ ;  $t_{11} = -1.86$ ,  $P = 0.045$ ). Furthermore, it could not be accounted for by S.M.'s degree of familiarity with the experimenter (see **Supplementary Text** for detailed results).

Throughout the experiment, S.M. demonstrated a notable lack of discomfort at close distances. For example, on one trial, she walked all the way toward the experimenter to the point of touching, and she repeatedly stated that any distance felt comfortable. We quantified this by asking her to rate her degree of discomfort (1, perfectly comfortable; 10, extremely uncomfortable) while one of us stood facing her at various distances. Even when nose-to-nose with direct eye contact, S.M. rated the experience a 1. In a more natural and unexpected context, a completely unfamiliar male confederate stood abnormally close to her while engaging in conversation; S.M. again rated the experience a 1. By contrast, the confederate rated his experience a 7. Although S.M. indicated afterward that she knew we were “up to something,” awareness that this was an experiment cannot explain her lack of discomfort, since the confederate had complete awareness yet still found the experience to be highly uncomfortable.

At a cognitive level, S.M. understood the concept of personal space. She spontaneously stated that she did not want to make the experimenter uncomfortable by standing too close, and also stated that she believed her personal space was smaller than most. Furthermore, we asked S.M. to position the experimenter at the distance she judged other people might feel most comfortable. Although she considerably underestimated this distance ( $0.47 \pm 0.03$  m), her estimation was 38% greater than her own personal preference, thus demonstrating that she is aware that other people have personal space requirements different from her own. The fact that S.M. had a nonzero distance preference at all may simply reflect typical sensory processing constraints (for example, too close makes it more difficult to focus on the person).

Our findings in S.M. made a clear prediction regarding the amygdala in healthy individuals: its activity should be modulated by

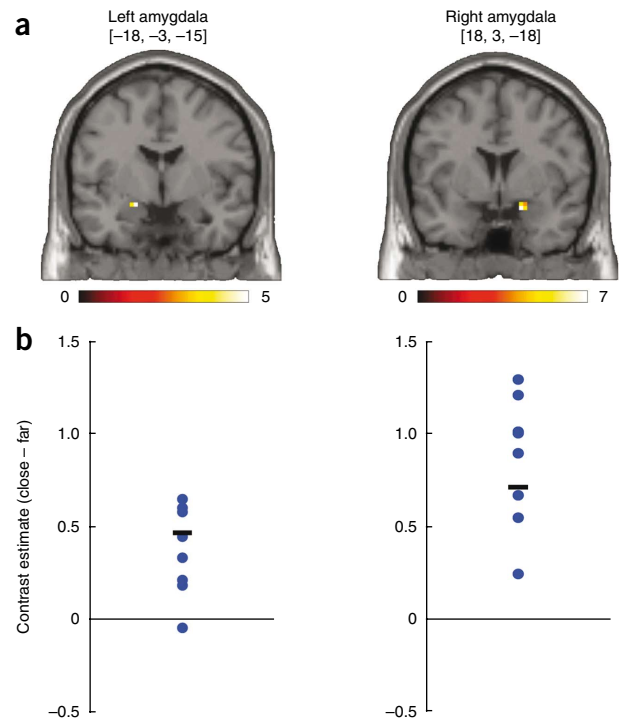


**Figure 1** Lesion study: mean preferred distances from the experimenter. (a) Preference of S.M. (red) was the closest distance to the experimenter (black), among age-, gender-, race- and education-matched controls (purple,  $n = 5$ ), as well as general comparison subjects (blue,  $n = 15$ ). (b) S.M.'s mean preferred distance from the experimenter (image drawn to scale). (c) Control participants' mean preferred distance from the experimenter, excluding the three largest outliers (image drawn to scale).

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**Figure 2** fMRI study: activation of the amygdala by close (relative to far) interpersonal distance. **(a)** Coronal slices showing significantly activated voxels in the dorsal amygdala (cluster-level significance,  $P < 0.05$ ); scale shows  $t$ -value. **(b)** Contrast parameters (arbitrary units) for each of the eight subjects who participated in the experiment (extracted from and averaged across all significant voxels in **a**; blue dots), along with the group mean (black line). Coordinates for the peak voxel are shown. Subjects were unable to see the position of the experimenter, but were informed of his location at all times. All experiments were approved by the California Institute of Technology's Institutional Review Board, and informed written consent was obtained from all participants. See **Supplementary Text** for a detailed description of the experiment.



Note: Supplementary information is available on the Nature Neuroscience website.

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#### AUTHOR CONTRIBUTIONS

D.P.K. and R.A. designed the experiment and wrote the paper; D.P.K. executed the studies; D.P.K., J.G. and J.M.T. analyzed the data.

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interpersonal distance. As a preliminary test of this prediction, and to obtain corroborating evidence, we conducted a functional magnetic resonance imaging (fMRI) study in eight healthy participants. We found that the amygdala responded to a greater degree when the participants knew an experimenter was maintaining a close distance to them (standing immediately next to the scanner) than when they knew an experimenter was maintaining a far distance. This effect was statistically significant at the group level (**Fig. 2**; see **Supplementary Text** for details). Although we did not collect ratings of subjective comfort from S.M. or control subjects on the protocol used in this fMRI study, our interpretation of the observed amygdala activation is that it reflects the same amygdala-dependent mechanism that comes into play when our personal space is noticeably violated.

In sum, we found that the amygdala was differentially activated by proximity to another person, and that complete bilateral damage to this structure in S.M. resulted in the absence of a detectable personal space boundary and an abnormally small interpersonal distance preference. In various animal species, many social behaviors (including collective group organization and consensus decision-making) can be modeled as a balance between attractive and repulsive forces between individual members of a group<sup>8,9</sup>. Our findings suggest that the amygdala may mediate the repulsive force that helps to maintain a minimum distance between people. Further, our findings are consistent with those in monkeys with bilateral amygdala lesions, who stay within closer proximity to other monkeys or people<sup>4,5</sup>, an effect we suggest arises from the absence of strong emotional responses to personal space violation.

One open question concerns how this mechanism might develop in infants and young children. It is possible that the amygdala is necessary for learning the association between close distances and aversive outcomes rather than triggering innate emotional responses to close others. As the developmental course of S.M.'s lesion is unknown, her data cannot distinguish between these two possibilities. A second open question is how this mechanism can accommodate modulation by situational context, personal familiarity and other factors<sup>2,10</sup>. Furthermore, there are variations in social distance between individuals, and gross dysregulation in disorders such as autism and Williams syndrome. These effects could arise in part through modulation of the amygdala from the prefrontal cortex, an effect of considerable recent interest in explaining individual differences and psychiatric disease<sup>11</sup>.

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### **Supplementary Text**

#### Lesion study:

All participants were tested in the same room by the same experimenter. Care was taken to ensure that the experimental setup remained identical across participants. We compared SM to 20 neurologically and psychiatrically healthy individuals recruited from the community (6 males; mean age =  $36.8 \pm 9.9$  years, range = 21.9-51.0, 10 Caucasian, 3 African-American, 4 Asian, 1 Hispanic, 2 Other). This included a subgroup of 5 controls matched to SM on age, gender, race, and level of education.

Subjects were asked to stand with their toes on a line that was marked on the floor while the same female experimenter walked at a natural gait towards them. Subjects were asked to tell the experimenter to stop at their preferred distance. This was fine-tuned as subjects could have the experimenter move slightly further backward or forward. The final distance was measured with a digital laser measurer (Bosch, model DLR165K, error  $\pm 0.003$ m).

All subjects completed a total of 32 trials. In the first 16 trials, the experimenter was always the one moving, and in the second 16, the subject was always the one moving.

Within each half, each trial type was repeated 4 times. All trials were administered in a fixed order. There were no gender effects in the controls.

To quantify statistically SM's abnormal interpersonal distance preference for the main trial type of interest (see Main Text), we first removed the 3 largest outlier subjects (see **Fig. 1a**), even though these data points are in support of our claim that SM has an unusually small distance preference. The t-values reported in the main text were calculated using a modified t-test procedure, suitable for comparing data from a single subject with a small normative sample<sup>1</sup>.

To ensure that SM's abnormal distance preferences were not due to familiarity effects, we tested 2 additional participants matched for SM's level of familiarity with the experimenter (as well as for gender and race). Both subjects preferred greater distances than did SM ( $0.56 \pm 0.04\text{m}$  and  $0.78 \pm 0.08\text{m}$ , collapsed across all trial types). Even a close friend of the experimenter preferred a distance ( $0.64 \pm 0.04\text{m}$ ) greater than did SM, who knew the experimenter for less than 1 week. Furthermore, SM's distance preference did not change with a familiar male experimenter ( $0.34 \pm 0.02\text{m}$ ) or with a less familiar male experimenter using an abbreviated version of the experiment ( $0.33 \pm 0.03\text{m}$ ).

We carried out additional versions of the main experiment. SM's abnormal distance preference was confirmed across each variation [starting close together and withdrawing vs. starting apart (SM =  $0.36 \pm 0.04 / 0.34 \pm 0.03\text{m}$  (mean  $\pm$  standard deviation), controls =  $0.81 \pm 0.29 / 0.75 \pm 0.29\text{m}$ ); eye-contact vs. no eye-contact (SM =  $0.34 \pm 0.03 / 0.36 \pm 0.04\text{m}$ , controls =  $0.78 \pm 0.28 / 0.78 \pm 0.28\text{m}$ ); subject moving vs. experimenter moving (SM =  $0.36 \pm 0.02 / 0.34 \pm 0.04\text{m}$ , controls =  $0.81 \pm 0.31 / 0.76 \pm 0.27\text{m}$ ); values reported are collapsed

across the other factors; all conditions together (SM =  $0.35 \pm 0.03\text{m}$ ; controls =  $0.78 \pm 0.29\text{m}$ ).

A 3-way ANOVA with control subjects (excluding the 3 outliers) revealed significant main effects of starting position [ $F(1,16)=112.8$ ,  $p<0.001$ ] and person moving [ $F(1,16)=22.25$ ,  $p<0.001$ ], but not eye contact [ $F(1,16)=0.37$ ,  $p=0.55$ ], on interpersonal distances. Control participants preferred significantly larger interpersonal distances when starting close compared to starting far apart (mean difference =  $0.062 \pm 0.02\text{m}$ ; range =  $0.025$  to  $0.122\text{m}$ ). SM failed to show this relative difference across conditions, and actually showed the smallest difference between these two conditions out of any participant (difference =  $-0.018 \pm 0.015\text{m}$ ;  $Z=-1.82$ ,  $p=0.034$ ;  $t(16)=-1.77$ ,  $p=.048$ , one-tailed). Control participants also preferred significantly larger distances when they approached the experimenter compared to when the experimenter approached them (mean difference =  $0.039 \pm 0.03\text{m}$ ; range =  $-0.024$  to  $0.14\text{m}$ ). Here, SM's relative difference across these conditions was not significantly different from controls (difference =  $0.022 \pm 0.02\text{m}$ ,  $Z=-0.50$ ,  $p=0.31$ ;  $t(16)=-0.45$ ,  $p=0.33$ , one-tailed), though only 3/17 subjects demonstrated less of a difference than her.

#### FMRI study:

In order to provide converging evidence for the role of the amygdala in interpersonal distance, we recruited 8 neurotypical males from the Los Angeles area for participation in an fMRI study (mean age = 29.2 years; range = 18-44 years; 5 Caucasian, 1 African American, 1 Hispanic, 1 Asian). We explained to the participants that we were interested in examining how the brain responds to knowing that another person is either

close to them or far from them. They were told that an experimenter would actually be in the MRI room with them at all times, and that the experimenter would be at 1 of 3 pre-defined locations. The position of the experimenter would be relayed to the participant via text on the screen and a person speaking to them via MRI-compatible headphones, but that they would not be able to see the experimenter. We explained to subjects that this was because we were “not interested in how the brain responds to the sight of someone at various locations, but rather, how the brain responds to knowing that someone was at various locations.” All participants understood this explanation, and were reassured that no deception would be used at any time during the experiment (which was true). They were told that their task was simply to be fully aware of the location of the experimenter, relative to their position, at all times, and to be aware of how they felt. There was no mention of the words “discomfort” or “personal space” at any time, and none of these participants participated as controls for the behavioral experiment.

Before scanning, the procedure was explained and acted out in a mock scanner room. During this demonstration (but not during the real experiment), participants were able to see the location of the experimenter. Once lying down and with their head just inside the opening of the mock scanner, the 3 positions were described and shown to the participants. The “Home” position was where the experimenter would be for the majority of time. We chose to include this baseline condition to make the occurrence of the close and far events less common, thus reducing effects of habituation and boredom. This “Home” position was roughly 8 feet away from the junction between the patient table and the opening of the magnet and at a 45° angle away. The “Far” position was approximately 15 feet directly in front of the opening of the magnet. The “Close” position was right at the

junction of the patient table and opening of the magnet, as close as one could stand without touching the patient or the scanner.

After this explanation, participants were introduced to the two experimenters that would be in the scanner room with them (one each during each of the repetitions of the experiment). Because being set-up for scanning often involves physical closeness (and possibly an invasion of one's space), a third person prepared each participant for scanning, so as to limit habituation of closeness to either of the two experimenters. Once in the magnet, a black cloth made from raincoat material was secured to the opening of the bore to block light from passing through, thus preventing participants from seeing the experimenter. Lastly, before scanning began, the experimenter in the room went to the back of the magnet (where the subject was able to see via a mirror) to identify himself as the experimenter for that particular functional run. After scanning, all subjects reported that they maintained awareness of the location of the experimenter at all times.

All MRI data were acquired using a 3 Tesla Trio (Siemens Medical Solutions, Malvern, PA) at the Caltech Brain Imaging Center. Functional data were collected using a T2\*-weighted echo-planar imaging sequence with the following parameters: 33 axial slices, interleaved acquisition, repetition time (TR) = 2000ms, echo time (TE) = 30ms, flip angle = 71° (Ernst angle assuming T<sub>1</sub> of gray matter is 1800ms), slice thickness = 3 mm with no gap, and in-plane resolution of 3 mm<sup>2</sup>. Each of the two functional runs lasted approximately 4 minutes. In each run, there were 5 "Close" events, 5 "Far" events, and 11 "Home" events. Both the "Close" and "Far" events each lasted 8 seconds, and the duration of the "Home" event was jittered (10, 12, 14, or 16 seconds; mean = 13 secs). The order of "Close" and "Far" conditions were randomized, and always interleaved with the "Home"

condition. To ensure subjects remained awake throughout the study, we monitored their eyes with an MR-compatible ASL eyetracker (Applied Science Laboratories; Bedford, Massachusetts). Immediately following the functional scans, a dual gradient echo sequence was used to acquire  $B_0$  fieldmap data to allow for retrospective correction of spatial distortion.  $T_1$ -weighted anatomical images were also acquired using a volumetric MP-RAGE sequence (176 sagittal slices, isotropic voxel size = 1 mm<sup>3</sup>).

Functional analyses were carried out using SPM5 (<http://www.fil.ion.ucl.ac.uk/spm>). Images for each functional run were pre-processed as follows: the first 2 images were discarded to avoid  $T_1$  saturation effects, corrected for timing of slice acquisition, aligned to the first image of each session and then aligned across sessions (thus yielding subject-specific movement parameters),  $B_0$  fieldmaps were used to correct for spatial distortion and for susceptibility-by-motion interaction<sup>2</sup>, spatially normalized to an EPI template in MNI space<sup>3</sup>, and smoothed with a full-width half-max Gaussian filter of 6 mm. First level design matrices included box-car regressors for both “Close” and “Far” conditions convolved with a canonical hemodynamic response function (HRF), along with movement parameters. Our contrast of interest was “Close – Far”, which estimates the brain response to close relative to far interpersonal distances for each individual subject.

These “Close – Far” contrast images were entered into a second-level random effects analysis (1-sample t-test) to assess the significance of amygdala activation across the group using an ROI analysis. The amygdala was defined bilaterally using the Anatomical Automatic Labeling (AAL) template<sup>4</sup>, and implemented via the WFU Pickatlas<sup>5</sup> (Version 2.4). Our statistical threshold was set at a cluster-level threshold of  $p < 0.05$ , computed

using an iterative Monte Carlo simulation program (AlphaSim; from Analysis of Functional NeuroImages<sup>6</sup>, version AFNI\_2007\_05\_29\_1644).

Significant effects were found in both the left and right amygdala (**Fig. 2a**). There was greater amygdala activity in the “Close” condition relative to the “Far” condition. The contrast estimates were then extracted from all significant voxels in both the left and right amygdala (**Fig. 2b**) to show how each individual subject contributed to the overall effect.

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