Using machine learning to track dogs' exploratory behavior in presence and absence of their caregiver

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Abstract

The dog-human relationship exhibits characteristics of human attachment bonds. In particular, dogs have been found to show a secure base effect, i.e., they explored and played more in the presence of their owner as compared to a stranger. In the current study, we presented the dogs with a procedure in which the dogs could move freely in a room equipped with trial-unique objects. We manipulated across trials whether the owner and/or a stranger was present in the room or not. Crucially, we applied and validated machine learning to track the dogs' behavior throughout the trials. The three-dimensional (3D) tracking of the dogs' bodies allowed us to extract behavioral responses with high spatial and temporal resolution without relying on subjective human ratings. The results show that both the owner and stranger significantly increased the dogs' exploration; the dogs also spend more time in the proximity of the owner and stranger location when they were present. Even though the presence of owner and stranger had a significant effect on the dogs' behavior, the effect of the owner was more pronounced. We conclude that machine-driven 3D tracking provides a reliable access for detailed behavioral analyses of dogs' exploration and attachment-related behaviors.

Keywords: attachment, 3D body tracking, exploration, canine cognition, separation problems, tail wagging

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Human (and nonhuman) infants develop a particular, affectional bond with their primary caregiver, known as attachment bond (e.g., Ainsworth, 1979; Bowlby, 1958; Suomi, 2008). The attachment figure serves as a secure base for exploring the environment and if necessary as a safe haven when presented with stressful situations (e.g., Ainsworth, 1979; Ainsworth & Bell, 1970; Waters & Cummings, 2000). The provision of security and comfort is a core feature of attachment setting it apart from other affectional bonds (Ainsworth, 1989). The benchmark test for studying attachment is the so-called strange situation test (Ainsworth & Bell, 1970). In this test developed for human infants, the following sequence of events are typically conducted in a fixed order: the caregiver carries the infant into a room, puts the infant down, and after some time, a stranger enters the room. The stranger first behaves quietly, then talks to the caregiver, and approaches the infant with a toy. Next, the caregiver leaves the room for up to three minutes while the stranger stays in the room. Then the caregiver returns and the stranger leaves. Once the infant is engaged in play again, the caregiver leaves and the infant is alone in the room for three minutes. Then the stranger returns and after another interval leaves again and the caregiver returns. While there are marked individual differences (Ainsworth, 1979), infants typically explore and play more in the presence of their caregiver (secure base effect) and show more signs of distress and less exploration in the absence of the caregiver. When reunited with the caregiver, infants show more proximity seeking and contact maintaining behaviors (Ainsworth & Bell, 1970).

A question that arises is whether attachment is specific to infant-caregiver relationships. An interesting model system to address this question is the dog-human relationship. Over the

course of their domestication, dogs adapted to the human environment and, as companion animals, they grow up and live in close proximity to their caregivers. As mentioned before, one of the central features of the attachment bond is the secure base effect (Waters & Cummings, 2000). When tested with the strange situation procedure, pet dogs, like infants, showed more exploration and play in the presence of the owner (compared to the stranger) and proximity seeking behavior toward the owner when the owner re-entered the room (Mariti et al., 2013; Palestini et al., 2005; Palmer & Custance, 2008; Prato-Previde et al., 2003; Topál et al., 1998). They also stood by the door more when the owner was outside than when the stranger was outside of the room (Mariti et al., 2013; Palmer & Custance, 2008; Prato-Previde et al., 2003; Topál et al., 1998) and played less with the stranger when the owner was gone (Mariti et al., 2013; Palestini et al., 2005; Palmer & Custance, 2008; Prato-Previde et al., 2003). Some studies argued that order effects could account for dogs' presumed secure base effect (Prato-Previde et al., 2003; Rehn et al., 2013): the dogs were first alone with their owner and might have engaged more in exploration because the room was new to them. Accordingly, when the stranger later entered the room, the dogs showed lower levels of exploration because they had already completed the exploration of the room. However, other studies provided evidence for secure base effects (i.e., more exploration, individual play, and social play with the stranger in the presence of the owner) even when the order of conditions was counterbalanced (Palmer & Custance, 2008). In line with these results, in other paradigms (in which the order of conditions was also counterbalanced) the owner's presence, unlike a stranger's presence, increased the dogs' manipulation times of toy objects (Cimarelli et al., 2021; Horn, Huber, et al., 2013).

Dogs, like human infants, can be categorized into different attachment styles (Schöberl et al., 2016; Solomon et al., 2019; Thielke & Udell, 2019). Securely attached dogs were found to

77 have a lower cortisol reactivity than insecurely attached dogs during attachment and play
78 situations (Schöberl et al., 2016). Differences in behavior depending on the owner's presence
79 have also been supported by heart rate measurements (Fallani et al., 2007; Gácsi et al., 2013;
80 Palestirini et al., 2005). For example, in one such study a stranger approached the dog in a
81 threatening manner either in the presence or absence of the owner (Gácsi et al., 2013). Dogs
82 reacted to the threat with an increased heart rate but this effect was less pronounced in the
83 presence of the owner. The finding was interpreted as evidence for a safe haven effect, i.e. for a
84 security providing role of the owner (see also, Cimarelli et al., 2016).

85 Another characteristic of attachment bonds is the specificity to the primary caregiver. The
86 comparison between the primary caregiver and the stranger does not address this issue because
87 any difference in the dogs' reactions might be merely due to differences in familiarity. The
88 comparison between familiar humans and the primary caregiver has revealed that dogs indeed
89 react differently to their primary caregiver compared to a familiar person (Horn, Range, et al.,
90 2013; Huber et al., 2013; Karl et al., 2020; Kerepesi et al., 2015). Dogs have been found to
91 distinguish between their owner and a familiar person particularly in situations designed to
92 assess social relations and attachment (i.e., when the dogs were presented with a threatening
93 stimulus or when the owner or familiar person tried to initiate playful interactions) and less in
94 obedience-related situations (Kerepesi et al., 2015).

95 The extent to which animals engage in exploration is not only determined by the presence
96 of an attachment figure but also by their attitudes toward novelty (i.e., neophobia / neophilia).
97 Dogs have been described as neophilic, that is, when presented with a novel toy among familiar
98 ones pet dogs preferentially chose the novel toy (Kaulfuß & Mills, 2008). A comparison between
99 hand-raised wolves (*Canis lupus*) and dogs raised and kept in the same way revealed that dogs

were less neophobic but also showed less interest in novel objects than wolves (Moretti et al., 2015). Object exploration in both species was facilitated in the presence of conspecifics.

In the current study, we studied the extent to which pet dogs explored a room with novel objects depending on the presence or absence of their primary caregiver and a stranger. In contrast to the strange situation procedure, both caregiver and stranger did not directly interact with the dogs during the experiment. Besides, previous studies relied on video scorings of human observers. The main contribution of the current study is that we measured the dogs' exploration without relying on subjective human ratings by applying machine-learning-driven 3D body tracking. In particular, we tracked eight different key point of the dogs' body and extracted measures of the dogs' movement pattern, object exploration, tail wagging, and visual orientation. Based on the previous literature, we predicted that the dogs would spend more time in the proximity of their owner and that they would move (travelling distance) and explore more (area covered, minimal distance to objects) in the presence of the owner (Mariti et al., 2013; Palestini et al., 2005; Palmer & Custance, 2008; Prato-Previde et al., 2003; Topál et al., 1998). Previous research also found a facilitating effect of strangers on the dogs' exploration even though to a lesser degree compared to the owner (Mariti et al., 2013; Palmer & Custance, 2008). Moreover, we predicted more tail wagging in the presence of the owner (Mariti et al., 2013; Quaranta et al., 2007). For their head orientation (visual angle), we predicted that the dogs would overall face more to the owner (Prato-Previde et al., 2003).

120 **Methods**

121 **Subjects**

122 We tested 37 pet dogs of various breeds (including mixed-breed dogs) with a minimal
123 shoulder height of 45 cm (mean age: 75 months; range: 11-182; 19 females; 18 males). The
124 sample size was similar to previous studies looking at the effects of owner presence on dogs'
125 exploration (e.g., Mariti et al., 2013; Palmer & Custance, 2008). Our planned sample size was 48
126 dogs, which we did not reach due to restrictions imposed due to the SARS-CoV-2 pandemic. All
127 owners were recruited using the Clever Dog Lab database and via social media.

128 **Ethics statement**

129 The participation was voluntary and the procedure itself was non-invasive and short. The
130 study was discussed and approved by the institutional ethics and animal welfare committee in
131 accordance with GSP guidelines and national legislation (approval number ETK-102/06/2020).
132 Written consent by the dog owners was obtained prior to the data collection.

133 **Experimental set-up**

134 The experiment took place in a testing room (sized 6 m x 7 m) of the Clever Dog Lab in
135 Vienna (Figure 1). The room had two doors on one side and two windows on the opposite side of
136 the room. The room was equipped with six HD cameras (Panasonic HC-V777) mounted in the
137 four corners and in the centre of the long sides of the room (close to the ceiling). We placed two
138 chairs in the room, facing each other (henceforth chair A, located between the entrance doors and
139 chair B, located between the windows). The chairs were placed close to the middle of the longer
140 walls of the room. We placed four planks made of grey PVC (50 x 50 cm) in the centre of the
141 room at predefined locations, equidistant to each other. We attached stripes of rubber to the
142 bottom of each plank to increase friction, ensuring that the planks remained in place. We used 16

common household objects to enrich the environment and to elicit exploratory behaviour. Before the beginning of each trial, we placed the objects on the planks. We used Velcro tape to attach objects to the planks and to enable a quick removal from and reattachment to the planks. The objects varied between the trials, so the dogs were presented with four new objects in every trial of the experiment. We counterbalanced the assignment of the objects to conditions across dogs.

Figure 1 (A) Picture of the setup (without the barriers that were placed next to the chairs), (B) Screenshots of the six camera views showing a dog exploring one of the objects in the owner present condition. The tracked key points are overlaid on the videos.

Design

We used a 2x2 within-subjects design. We manipulated whether the owner was present (e.g., sitting on chair A) or not and whether a stranger was present (e.g., sitting on chair B) or not while the dogs could explore the room. This design resulted in four different conditions: owner-

present (stranger absent), stranger present (owner absent), both present, both absent. We counterbalanced the order of condition as well as assignment of the chairs to the owner / stranger across dogs.

Procedure

We conducted one trial per condition with each dog. All trials were conducted within a single session. The order of conditions was pseudo-randomized across dogs, so that the frequencies of the possible orders were finally counterbalanced. Each trial lasted 120 seconds.

In the owner-present conditions, the owner entered the unfamiliar room (through the right door) with the dog leashed and walked to the centre of the room. The owner then unleashed the dog and took a seat on the assigned chair. The owner was instructed not to interact with the dog in any way. The owner was also asked to hold a magazine (placed on the assigned chair prior to the owner's entry) in front of their face and to (pretend to) read it to prevent eye contact with the dog. In the owner-absent conditions, the owner entered the room through the same door with the dog leashed and walked to the centre of the room. The owner then unleashed the dog and left the room (through the same door). The owners were instructed not to pay attention to the dog when leaving. In few instances, if the dog closely followed the owner while the owner was leaving the room, the owner was allowed to make a hand gesture for the dog to stay in the room.

Apart from the owner's presence, we also manipulated the presence of a stranger. In the stranger-present conditions, the stranger was instructed to sit on the assigned chair and follow the dog with her/his gaze whilst retaining a natural facial expression. The identity of a stranger varied across dogs (four female and two male strangers participated in the study). The stranger entered and left the room in between trials through the left door (unseen by the dog).

After the fourth trial, the owners were asked to walk around the room for 20 seconds. These short videos were used (along with the both present videos) as training data for the machine learning algorithm. Finally, measures of distances between snout and the centre of the head, centre of the head to each ear, and the distance between the ears were taken using a measuring tape. These measurements were later used to evaluate how well the reconstructed distances (derived from the 3D reconstruction) matched the real-world measures.

In addition, each owner was asked to fill out parts of the C-BARQ (Hsu & Serpell, 2003) before participating in the study. The edited version only contained sections: 3 – Fear and anxiety, 4 – Separation-related behaviour, and 6 – Attachment and attention-seeking.

3D body tracking

We used machine learning to track different key points of the dogs' bodies to examine their exploratory behaviour. We used the video analysis software Loopy (<http://loopb.io>, loopbio gmbh, Vienna, AUSTRIA) for the annotation of videos, deep learning based key point detection and the 3D reconstruction of key points based on video collections of the same scene filmed from six different camera positions.

Calibration and alignment

Before recording the test videos, we determined the orientation of the cameras (which was kept constant throughout the study) and calibrated the camera system. We carried out two types of calibrations. The intrinsic calibration provided information on 2D parameters, focal length and lens distortion to the software. The second, extrinsic calibration provide information on 3D parameters and on the spatial relations between the cameras. The extrinsic calibration involved taking a video with all six cameras of a person walking through the room and moving a LED light attached to a short rod. Finally, we measured distances between landmarks in the room

(corners, edges, etc.) and created a 3D model of the room based on these measurements. These measurements were then used to align the real-world distances to the virtual coordinate system provided by the software. This allowed us to collect data on the position of each key point in real-world coordinates (in meters) relative to a landmark (a marking on the floor that was set as the origin of the coordinate system) close to the centre of the room.

Key point detector

We annotated two videos per dog, namely the videos of the both-present condition (owner and the stranger present in the room) and videos showing the dog and owner walking around in the room. We selected these videos because they showed the dogs from different angles and at varying positions in the room while other moving stimuli (owner and stranger) were present in the room. Next, we selected eight key points on the dogs' body for the annotation: snout, head centre, right ear, left ear, base of neck (atlas region), hip region, base of the tail, and the tip of the tail (Figure 2). In total, we annotated 468 videos of 38 dogs (two recordings per dog as well as four recordings of a pilot dog, with 6 camera views per recording) and for each video, we annotated one frame per second (which resulted in ca. 20 frames per walking video and 120 frames per both-present condition video). These annotations were then used to train a key point detector (with the following parameters in Loopy: input network size=1344x756, stride=4, training iterations=150 000). This key point detector was used to create predictions for all videos (except the walking videos) from which a 3D-reconstruction was created.

Data processing and analysis

We conducted the following data processing steps to remove incorrect detections and to account for missing data: First, we removed unrealistic values (i.e., coordinates outside of the

room and coordinates higher than 1.5 m). Then we calculated the average coordinates across the different key points for each video frame and excluded the coordinates of the individual key points that deviated more than 1 m from these average coordinates to eliminate cases when a single key point was detected incorrectly (e.g., when the tip of a shoe of the stranger or owner was detected as the snout of the dog). Next, we filtered out the data points that deviated more than 1.5 m in any dimension from one frame to the next or the previous one (the videos had a frame rate of 24 fps). We then performed a linear interpolation to fill in the missing data and filtered out the data that deviated more than 20 centimetres in any dimension from one frame to the next followed by a linear interpolation of the missing data. The last step (filtering followed by interpolation) was repeated three more times. Finally, we calculated a rolling average (with a rolling window size of 3 frames) to further smoothen the trajectories (see Figure 2A for an example).

For each dog, condition, and key point, we calculated the following variables from the processed (filtered and interpolated) data: the proportion time the dogs spent in different interest areas (IA) in front of the owner and stranger chairs and in front of the two doors (owner IA and stranger IA: 2 m x 1.4 m, door IAs: 1 x 1 m at each door; see Figure 4A), the travelled distance and the average minimal distance from the four objects on the floor. Additionally, we calculated the area of the room visited by the dogs. This area was determined by overlying the floor plan with a virtual grid consisting of 50 x 50 cm cells and determining the proportion of grid cells visited by the dogs. Based on the proportion of tracked data and how subjectively easy we judged the annotation of the key point locations, we decided to use the head centre key point for these analyses.

Furthermore, we calculated the 3D angle between the dogs looking direction and the owner chair. The looking direction was approximated based on the head-centre—snout axis (assuming that the eye position is in the middle between the two key points and the looking direction is elevated by 45° relative to the head-centre—snout axis). Finally, as a measure of tail wagging, we calculated the ratio of the travelling distance of the tail tip and the travelling distance of the tail base.

We analysed the log-transformed travelling distance and average minimal object distance of the head centre key point by fitting a linear mixed model (LMM; fitted using R (R Core Team (2021)) package lme4 (Bates et al, 2015)). We checked the assumptions of homogeneous and normally distributed residuals by visually inspecting the residuals against fitted data and the Q-Q plot of the residuals; we found no obvious violations of the assumptions.

All other response variables were analysed as proportions using a generalized linear mixed model (GLMM) with beta error structure (fitted using R package glmmTMB (Brooks et al, 2017)). We scaled the response variables by dividing them by the maximum value to obtain values between 0 and 1. Beta regression models allow to model variables with values between 0 and 1; therefore, we transformed the data so that they did not comprise the extreme values 0 and 1 (Smithson & Verkuilen, 2006). For all models, we checked for overdispersion, which was not an issue (max. overdispersion parameter: 1.17).

In all models, we included test predictors owner presence, stranger presence, and their interaction as well as the control predictors trial number, age, and sex. Moreover, we included the random intercept of the subject ID as well the random slopes of owner presence, stranger presence, and trial number within subject ID. All models were weighted on the proportion of tracked data. We first made sure that the full model fitted the data significantly better when

compared to a null model only including control predictors (trial number, age, and sex) and random effects. We used likelihood ratio tests (using R functions ‘drop1’ with the argument test set to “Chisq”) to calculate the p-values.

We also checked for collinearity by calculating variance inflation factors using the library ‘car’ (Fox & Weisberg, 2019). Collinearity was no issue (max. VIF: 1.04). In case of convergence issues, we pruned the model in the following sequence: we first removed the random slope of the control variable trial number. Then we removed the control predictors, first sex then age. Finally, we removed the random slopes of the stranger present conditions. If the full model converged but we encountered convergence issues when removing single predictor variables (to calculate the likelihood ratio tests), we used the Wald tests instead to draw inferences about the significance of the fixed effects.

Results

Validating the results of the key point detectors

We carried out the following steps to evaluate the accuracy of the key point detectors: First, we performed a visual assessment of the predicted key points overlaid on the video recordings (see supplementary video 01). We then calculated the proportion of tracked data (after all filtering steps and without considering interpolated values) for each key point by dividing the number of tracked frames by the total frame count (Table 1). The software provided information on the reprojection error, defined as the sum of the distance (in pixels; normalised by the number of cameras used for the reconstruction) between a detected point (2D point provided by the key point detector) and the reconstructed point (3D point reconstructed from 2D points of two or more cameras). Although, some key points were tracked more frequently, we chose head centre key point for our analysis because it was subjectively easier to locate during the annotations and

was tracked more accurately in the prediction videos (also evidenced by the low reprojection error).

Table 1 Proportion of tracked data per key point.

Key point	Median	Minimum	Maximum	Mean reprojection error ¹
Atlas	0.94	0.54	1.00	12.25
Head centre	0.86	0.06	1.00	9.78
Hips	0.98	0.20	1.00	12.97
Left ear	0.90	0.30	1.00	10.99
Right ear	0.92	0.50	1.00	10.37
Snout	0.75	0.15	1.00	10.86
Tail base	0.96	0.31	1.00	12.88
Tail tip	0.92	0.35	1.00	12.47

Notes: Values based on all runs, N=148; ¹Mean reprojection error of each key point. The reprojection error is the distance (in pixels) between a detected point (2D point provided by the key point detector) and the reconstructed point (3D point reconstructed from 2D points of two or more cameras)

We then calculated the average distance between the reconstructed snout and head centre key points and compared it to the measurements taken for each dog (Figure 2B). The measured and reconstructed head-snout distance were significantly correlated (Pearson correlation: $r(35) = .61, p < .001$).

We also examined the extent to which the travelling distances in each run correlated across the eight key points (see Figure 2C). We found high correlations ($\geq .9$) between all key points except for the tail tip. Correlations between the tail tip and the other key points were slightly lower (range: .74-.82), which was expected because the movements of the tail were not limited by the movement of the torso.

Figure 2(A) Exemplary data of one dog in the both present condition. The blue dots indicate areas visited by the dog. The green squares indicate the location of the doors, the dark grey squares the location of the chairs, and the light grey squares show the locations of the objects. (B) Comparison between measured and median reconstructed head-snout distance. The dots show the values measured for each dog. The lines connect the measured and reconstructed values of each dog. (C) Pearson correlations between the travelling distances calculated for each key point in each run ($N = 148$). All correlations were significant ($p < 0.001$).

C-BARQ scores

All owners were asked to fill out the shortened version of the C-BARQ (Hsu & Serpell, 2003; Ott, 2016). The shortened version included the questions regarding the C-BARQ subscales non-social fear, stranger-directed fear, separation-related problems, and attachment/attention

seeking behaviours. The average values of our sample matched the general population values well (Bowen et al., 2019; see Table 2).

Table 2 Summary of the shortened C-BARQ scores compared to the general population (based on 33,708 dogs) reported by Bowen et al. (2019)

	Non-social fear	Stranger-directed fear	Separation-related problems	Attention seeking
Mean $\pm$ SD	0.88 $\pm$ 0.66	0.55 $\pm$ 0.93	0.45 $\pm$ 0.56	1.90 $\pm$ 0.80
Range	0 - 2.33	0-3.75	0-2.29	0-3.17
General population	0.84 $\pm$ 0.77	0.67 $\pm$ 0.95	0.60 $\pm$ 0.66	2.01 $\pm$ 0.81

Correlations between the C-BARQ scores and the proportion time variables for the different IAs and conditions (Figure 3 and 4A) suggest that dogs with higher stranger fear or separation problems scores were more likely to visit the stranger IA when the stranger was absent. Moreover, dogs with higher non-social fear tended to stay in the owners IA for longer periods when no one else was in the room. However, these correlations were not corrected for multiple comparisons and should therefore be interpreted with caution (none of the correlations were significant if a correction for multiple comparisons was applied).

Figure 3 Pearson correlation matrix between C-BARQ subscales and proportion time spent in the different interest areas (owner, stranger, door). Blue shaded tiles indicate positive correlations, red tiles negative correlations. The p-values were not corrected for multiple comparisons; * $p < 0.05$, ** $p < 0.01$.

Figure 4 Plot showing the dogs (N=37) roaming pattern across the four conditions. The blue dots indicate areas visited by the dogs; darker blue areas were visited more frequently. The green squares indicate the location of the doors, the dark grey squares the location of the chairs, and the light grey squares show the locations of the objects. The red concentric lines show the contours of a 2D kernel density estimation; they highlight areas that were likely to be visited by the dogs. In the presence of the owner, these included the areas around the chairs, in the absence of the owner the door locations. The open rectangles show the interest areas (IA) in front of the doors and chairs for the proportion time analyses. (B)-(D): Box- and violin-plots showing the proportion time the dogs spent in the owner IA (B), stranger IA (C), door IAs (D) across the conditions. The dots represent mean individual values; O+ / O- indicates the presence / absence of the owner; S+ / S- indicates the presence / absence of the stranger.

Proportion time in owner IA

We fitted a GLMM (GLMM 01) for the proportion time in owner IA response variable and included the predictor variables owner presence, stranger presence, and the interaction between these two variables, trial, and age (full-null model comparison: $\chi^2(4) = 45.05, p < .001$). The interaction was not significant (owner presence: stranger presence: $\chi^2(1) = 1.73, p = .189$). In order to evaluate the main effects, we re-fitted the model without the interactions (GLMM 02;

full-null model comparison: $\chi^2(3) = 43.32$, $p < .001$, Table 3). The dogs spent more time in the owner IA when the owner was present than when the owner was absent (Figure 4 B). The stranger's presence, trial number, age, or sex had no significant effect.

Table 3 Results of GLMM 02 with proportion time in owner IA as the response variable.

	Estimate	SE	Z value	P
(Intercept)	-2.83	0.18	-15.43	<0.001
Owner presence	1.86	0.22	8.63	<0.001
Stranger presence	-0.18	0.12	-1.5	0.134
Trial number	0.05	0.07	0.71	0.481
Age	0.09	0.11	0.81	0.417
Sex	-0.1	0.24	-0.4	0.687

Notes: Reference categories: owner presence: absent; stranger presence: absent; sex: female. Covariates trial number and age centred and scaled to a standard deviation of 1.

Proportion time in stranger IA

We fitted a GLMM (GLMM 03) for the proportion time in stranger IA response variable and included the predictor variables owner presence, stranger presence, and the interaction between these two variables, and trial (full-null model comparison: $\chi^2(3) = 21.06$, $p < .001$; the control predictors age and sex were pruned due to convergence issues). The interaction was not significant (owner presence: stranger presence: $\chi^2(1) = 1.06$, $p = .289$). In order to evaluate the main effects, we re-fitted the model without the interactions (GLMM 04; full-null model comparison: $\chi^2(2) = 19.87$, $p < .001$, Table 4). The dogs spent more time in the stranger IA when the stranger was present than when the stranger was absent (Figure 4 C). Additionally, dogs spent less time in the stranger IA with increasing trial number. The owner's presence or had no significant effect.

Table 4 Results of GLMM 04 with proportion time in stranger IA as the response variable.

	Estimate	SE	Z value	P
(Intercept)	-3.6	0.27	-13.19	<0.001
Owner presence	0.01	0.27	0.05	0.957
Stranger presence	1.41	0.28	5.07	<0.001
Trial number	-0.39	0.08	-4.75	<0.001
Sex	-0.47	0.25	-1.92	0.055

Notes: Reference categories: owner presence: absent; stranger presence: absent; sex: female. Covariate trial number centred and scaled to a standard deviation of 1.

Proportion time in door IA

We fitted a GLMM (GLMM 05) for the proportion time in door IA response variable and included the predictor variables owner presence, stranger presence, and the interaction between these two variables, trial, and age (full-null model comparison: $\chi^2(4) = 69.76, p < .001$; the control predictor sex was pruned due to convergence issues). The interaction was not significant (owner presence: stranger presence: $z=1.25, p=0.211$). In order to evaluate the main effects, we re-fitted the model without the interactions (GLMM 06; full-null model comparison: $\chi^2(3) = 68.08, p < .001$, Table 5; the control predictors sex and age were pruned due to convergence issues). The dogs spent more time in the door IA when either the owner or the stranger was present (Figure 4 D). The trial number had no significant effect.

Table 5 Results of GLMM 06 with proportion time in door IA as the response variable.

	Estimate	SE	Z value	P
(Intercept)	0.17	0.27	0.61	0.543
Owner presence	-2.23	0.27	-8.38	<0.001
Stranger presence	-0.63	0.12	-5.34	<0.001
Trial number	0.12	0.07	1.65	0.100

Notes: Reference categories: owner presence: absent; stranger presence: absent. Covariate trial number centred and scaled to a standard deviation of 1.

Travelling distance of head centre

We fitted an LMM (LMM 01) to the travelled distance response and included the predictor variables owner presence, stranger presence, and the interaction between these two

variables, trial, sex, and age (full-null model comparison: $\chi^2(3) = 18.93$, $p < .001$). However, the interactions were not significant (owner presence: stranger presence: $\chi^2(1) = 0.11$, $p = 0.738$). In order to evaluate the main effects, we re-fitted the model without the interactions (LMM 02; full-null model comparison: $\chi^2(2) = 18.81$, $p < .001$; R^2 of full LMM: 0.80; Table 6). Dogs moved significantly more when the owner was present and also when the stranger (Figure 5 A) was present. Additionally, the dogs moved less with increasing trial number. Sex and age had no significant effects on the travelling distance.

Table 6 Results of LMM 02 with the travelled distance of the head centre key point as the response variable.

	Estimate	SE	Lower 95% CI	Upper 95% CI	χ^2	df	P
(Intercept)	3.28	0.13	3.02	3.56			
Owner presence	0.36	0.09	0.19	0.53	14.22	1	<0.001
Stranger presence	0.19	0.06	0.07	0.31	10.7	1	0.001
Trial number	-0.25	0.03	-0.31	-0.18	60.13	1	<0.001
Age	-0.09	0.08	-0.26	0.07	1.28	1	0.259
Sex	-0.06	0.15	-0.39	0.26	0.14	1	0.706

Notes: Reference categories: owner presence: absent; stranger presence: absent; sex: female. Covariates trial number and age centred and scaled to a standard deviation of 1.

Object exploration (minimal distance to the objects)

We analysed object exploration by fitting a LMM (LMM 03) with the average minimal distance to the four objects within a trial as response variable and including the predictor variables owner presence, stranger presence, and the interaction between these two variables, trial, sex, and age (full-null model comparison: $\chi^2(3) = 27.01$, $p < .001$). The interaction was not significant (owner presence: stranger presence $\chi^2(1) = 0.46$, $p = .499$). In order to evaluate the main effects, we re-fitted the model without the interactions (LMM 04; full-null model comparison: $\chi^2(2) = 26.55$, $p < .001$; R^2 of full LMM: 0.78; Table 7). The minimal distance between the key point head centre and the objects was smaller when the owner or the stranger

was present (Figure 5B). The females tended to approach the objects more closely than males.

The minimal distance grew with increasing trial number. The dogs' age had no significant effect.

Table 7 Results of LMM 04 with the minimal distance between the head centre key point and objects as the response variable.

	Estimate	SE	Lower 95% CI	Upper 95% CI	χ^2	df	P
(Intercept)	-0.26	0.08	-0.44	-0.1			
Owner presence	-0.40	0.08	-0.57	-0.25	19.86	1	<0.001
Stranger presence	-0.20	0.06	-0.32	-0.09	11	1	0.001
Trial number	0.25	0.03	0.19	0.31	59.18	1	<0.001
Age	0.04	0.05	-0.07	0.16	0.51	1	0.476
Sex	0.33	0.11	0.11	0.55	8	1	0.005

Notes: Reference categories: owner presence: absent; stranger presence: absent; sex: female. Covariates trial number and age centred and scaled to a standard deviation of 1.

Area covered

We fitted a GLMM with the proportion of area covered as response variable and including the predictor variables owner presence, stranger presence, and the interaction between these two variables, trial, sex (GLMM 7; full-null model comparison: $\chi^2(3) = 33.13$, $p < .001$). However, the interaction was not significant (owner presence: stranger presence: $\chi^2(1) = 0.25$, $p = .619$). In order to evaluate the main effects, we re-fitted the model without the interactions (GLMM 08; full-null model comparison: $\chi^2(2) = 32.88$, $p < .001$; Table 8). The dogs visited a larger proportion of the room area when the owner or a stranger was present (Figure 5 C). They covered less area with increasing trial number. Sex or age had no significant effect.

Table 8 Results of GLMM 08 with area covered as the response variable.

	Estimate	SE	Z value	P
(Intercept)	-1.55	0.16	-9.94	<0.001
Owner presence	0.6	0.1	5.78	<0.001
Stranger presence	0.21	0.07	3.28	0.001
Trial number	-0.46	0.03	-14.01	<0.001
Age	-0.09	0.1	-0.86	0.391
Sex	-0.31	0.2	-1.57	0.116

Notes: Reference categories: owner presence: absent; stranger presence: absent; sex: female. Covariates trial number and age centred and scaled to a standard deviation of 1.

Tail wagging

We fitted a GLMM (GLMM 09) for the tail wagging response variable and included the predictor variables owner presence, stranger presence, and the interaction between these two variables, trial, sex, and age (full-null model comparison: $\chi^2(3) = 20.82, p < .001$). The interaction was significant (owner presence: stranger presence: $\chi^2(1) = 5.37, p = 0.020$). Post-hoc tests (by releveling the reference categories of conditions) revealed that dogs moved their tail significantly more when either the owner or a stranger were present (both absent vs owner present: $z=2.17, p=0.030$; both absent vs stranger present: $z=4.45, p<0.001$; both present vs owner present: $z=0.60, p=0.550$; both present vs stranger present: $z=-1.41, p=0.158$; see Figure 5D). The trial number and the dogs' sex or age had no significant effect.

Table 9 Results of GLMM 09 with the ratio between distances travelled by tail tip and tail base key points (scaled to an interval between 0 to 1) as the response variable.

	Estimate	SE	Lower 95% CI	Upper 95% CI	χ^2	df	P
(Intercept)	-1.2	0.14	-1.49	-0.94			
Owner presence	0.26	0.12	0.01	0.52			
Stranger presence	0.47	0.11	0.24	0.69			
Trial number	0.05	0.04	-0.03	0.13	1.85	1	0.174
Age	-0.03	0.07	-0.16	0.11	0.19	1	0.665
Sex	0.11	0.13	-0.15	0.39	0.66	1	0.416
Interaction between owner and stranger presence	-0.33	0.14	-0.67	-0.03	5.37	1	0.021

Notes: Reference categories: owner presence: absent; stranger presence: absent; sex: female. Covariates trial number and age centred and scaled to a standard deviation of 1.

Visual angle

We fitted a GLMM for the average angle between the dogs' head direction and the owner chair and included the predictor variables owner presence, stranger presence, and the interaction between these two variables (trial, sex, and age were pruned due to convergence issues) but the full model did not provide a better fit to the data compared to the null model without the test predictors (GLMM 10; full-null model comparison: $\chi^2(3) = 4.12, p = .249$).

Figure 5 Box- and violin-plots showing different response variables across the conditions. (A) distance travelled of the head center key point (in m), (B) the average minimal distance to the four objects (in m), (C) the proportion of area visited by the subject, (D) the tail wagging ratio (scaled to values between 0 and 1 with higher values indicating more tail wagging), The dots represent mean individual values; O+ / O- indicates the presence / absence of the owner; S+ / S- indicates presence / absence of the stranger.

Discussion

Both the presence of the owner and stranger significantly affected the dogs' exploratory behaviour, movement profiles, and tail wagging in the current study. The dogs spent more time close to owner's chair when the owner was present but we also found a similar effect for the stranger (i.e., longer times in proximity of the stranger's chair when the stranger was present). The dogs spent more time close to the two doors particularly when the owner was outside of the room but also, even though to a lesser extent, when the stranger was outside of the room. With respect to their exploratory tendencies, the dogs moved more, visited a larger proportion of the room and inspected the objects more closely if at least one person was present. Additionally, the dogs moved their tail more when at least one person was present. While both owner and stranger had a significant effect on the dogs' behaviour, the effect of the owner was larger across the different behaviours (except in the case of tail wagging).

The impact of the stranger's presence on the dogs' exploratory behaviour is in line with previous studies examining the attachment bond between dogs and their caregivers. Aside from the owner's impact (known as secure base effect) also the stranger had a positive effect on exploration in dogs (Mariti et al., 2013; Palmer & Custance, 2008). Similar to previous results we also did not find evidence for stranger wariness in our sample of well socialised companion animals (Mariti et al., 2013; Palmer & Custance, 2008).

One might argue that the similar effect of the owner and stranger on the dogs' behaviour might have resulted from a sampling bias because dogs that participate in such studies might be particularly well trained and socialised. However, the C-BARQ scores of our sample did not provide evidence for this: we found C-BARQ scores in the current study that match those reported for a general dog population (Bowen et al., 2019).

We found no strong correlations between the dogs' behavioural responses and the C-BARQ questionnaire scores that refer to non-social fear, stranger fear, separation problems, or attention-seeking/attachment. There was some indication that the dogs that scored high on the stranger fear and separation-problems subscales explored the stranger's chair more when the stranger was absent and that dogs with higher non-social fear spent more time at the owner's chair when they were alone. However, our limited sample size and the modest correlations prevented us from drawing any strong conclusions here concerning the link between owner-ratings and behavioural measures. Another recent report found no evidence for an association between C-BARQ subscales and attachment styles in dogs either (Thielke & Udell, 2019; N = 52). A study using a larger sample (N = 697), however, provided evidence for small but significant correlations (correlation coefficients < 0.3) between a sociability trait measured in a behavioural test (stranger greeted the dog and the owner, took the dog for a short walk and finally examined the dog physically) and the stranger fear and aggression subscales of the C-BARQ (Svartberg, 2005). Our sample was too small to identify significant correlations of such small magnitude.

The effect of the owner's presence on the dogs' exploration (travelled distance, minimal object distance, area covered) and proximity seeking behaviour (proportion time in owner IA / stranger IA and door IAs) was larger than the stranger's effect in line with previous research (Mariti et al., 2013; Palmer & Custance, 2008; Prato-Previde et al., 2003; Topál et al., 1998). There were two exceptions: tail wagging and the average visual angle. First, for tail wagging the identity of the human did not seem to play a role (the dogs moved their tail more when they were not alone). A previous study using the strange situation procedure found that dogs moved their tail more when the dogs were reunited with their owner than with a stranger (Mariti et al., 2013)

but in the current study we did not look specifically at reunion events. Tail wagging in dogs is typically interpreted as affiliative behaviour (Bonanni et al., 2010). The left-right asymmetry of tail wagging has been related to emotional processing in dogs; a right-side bias has been associated with stimuli that elicit an approach response (Quaranta et al., 2007; Siniscalchi et al., 2013). In previous research, dogs showed a similar right-bias in their tail wagging for their owner and a stranger (Quaranta et al., 2007), though the amplitude of tail wagging was higher for the owner. In that study, the owner or stranger was revealed at the beginning of the trials by removing an opaque panel. Therefore, the procedure by Quaranta et al. also included a kind of reunion event in which the tail wagging was measured right after the dog was allowed to see their owner or someone else, which might explain the difference when compared to the current results.

Second, we found no significant evidence that the presence of the humans had a significant effect on the dogs' average visual angle. It is possible that a more fine-grained analysis would have yielded a different picture as any difference between conditions might have averaged out over time. On the one hand, in a previous study dogs spend more time oriented toward the owner (Prato-Previde et al., 2003). On the other hand, the secure base effect (Mariti et al., 2013; Palestrini et al., 2005; Palmer & Custance, 2008; Prato-Previde et al., 2003; Topál et al., 1998) predicts that in the presence of the caregiver dogs explore more and might therefore look more frequently away from the owner. The application of mobile eye-tracking and more fine-grained data analyses of the visual angle data might in the future reveal how dogs divide their visual attention between the caregiver, strangers, conspecifics, and other elements of their environment.

At a methodological level, our study demonstrates the feasibility and validity of 3D body tracking for behavioural research with dogs. The reconstructed distances mapped well on the real-world measures and the distances for the different key points were almost perfectly correlated with the expected exception of the tail tip (that moved to an extent independently from the rest of the body). A setup with more cameras will help to further increase the coverage of the room and thus the proportion of tracked key points.

Only a few canine behaviour studies to date applied machine-learning mediated tracking, most of them using tracking based on a single camera (e.g., Barnard et al., 2016; Bleuer-Elsner et al., 2019; Fux et al., 2021; Karl et al., 2020; Zamansky et al., 2018). These studies provided evidence that dogs with a deprivation syndrome moved less compared to normal controls when presented with a robot dog (Zamansky et al., 2018). Dogs with ADHD-like behaviors, in contrast, were found to cover larger proportions of a room, move faster, and re-orient more often compared to normal control dogs (Bleuer-Elsner et al., 2019). One study used a single depth camera for 3D body tracking with dogs housed in kennels (Barnard et al., 2016). Barnard et al.'s (2016) software identified four different behaviors (sit, lie, stand, locomotion) with high accuracy based on the 3D data.

In the current study, we included annotations of all 37 dogs in the sample. The annotations were a considerable effort: in total, ca. 32,760 frames per key point were annotated for the current study. Future research will reveal the extent to which the trained detectors can generalize to dogs that were not part of the training data or even to dog breeds that were not part of the training data.

Three-dimensional body tracking as applied in the current study is not completely free from human biases because the detectors are trained based on human annotations. However, one

can assume that the risk that the human observers systematically bias the extracted behavioral variables in a certain direction is lower in this case because during the annotation only the anatomical key points on the dog's body are identified and not, as in conventional behavioural scoring, the target behaviour itself.

In sum, our study shows that machine-learning driven 3D body tracking can be applied to measure canine exploration and attachment-related behaviours. Our study provided evidence that dogs moved more, approached novel objects more closely, visited larger parts of the room, and wagged their tail more if at least one person was present, highlighting the effect of human presence on dogs' exploratory behaviour. In line with this, dogs spend more time in the locations where the humans were sitting if the caregiver or stranger were present and also more time close to the door if one person was absent. Nevertheless, the effect on dogs' exploration was more pronounced in the case of the primary caregiver in support of a secure base effect (Mariti et al., 2013; Palmer & Custance, 2008; Prato-Previde et al., 2003; Topál et al., 1998). The C-BARQ scores suggest that our dog sample represented the general population well. Thus, dogs do not seem to react to a passive stranger with increased wariness but the stranger's presence has a rather similar effect (though less pronounced) effect compared to their primary caregiver. The 3D tracking methodology has proven to be a promising tool for studying canine cognition. Future research will reveal the extent to which it will also accelerate the extraction of behavioural data by generalising to new subjects and breeds.

Data accessibility

The data and R scripts associated with this manuscript are available on GitHub: github.com/cvoelter/dog_exploration_3Dtracking.

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Authors' contributions

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C.J.V. conceptualization, data curation, formal analysis, methodology, project administration, visualization, writing-original draft, writing-review and editing; D.S. conceptualization, investigation, annotation, data curation, formal analysis, methodology, writing-original draft, writing-review and editing L.H. conceptualization, funding acquisition, methodology, resources, writing-review and editing. All authors approved the final version of the manuscript.

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Competing interests

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We declare we have no competing interests.

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