Title
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Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 44(44)

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Publication Date
2022

Categorizing Dogs' Real World Visual Statistics

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Abstract

Dogs have a unique evolutionary relationship with humans and are relied upon in a variety of working roles, yet little is known about the kinds of visual information available to them, as well as how they direct their attention within their environment. The present study, inspired by comparable work in infants, aimed to categorize the visual statistics (specifically the identity of objects) available to dogs during a common event in their daily lives, a walk. Using a head-mounted eye-tracking apparatus that was custom designed for dogs, four dogs walked on a pre-determined route outdoors under naturalistic conditions generating a total of 49,431 frames for analysis. On average, there were few individual differences between dogs. Dogs looked proportionally more to people and plants than to other object categories in their environment, like the sky which they appeared to consider as background. The results of this project provide a foundational step towards understanding how dogs' look at and interact with their physical world, opening up avenues for future research into how they complete tasks, and learn and make decisions, both independently and with a human social partner.

Keywords: Domestic Dog; Eye-Tracking; Visual Attention; Preferential Gaze; Visual Statistics

Introduction

What does your dog see on a walk? What is visually interesting to them? Studying how individuals visually interact with the world, from their own perspective, gives insight into how they interact with the world in contexts ranging from a pet dog scanning for squirrels, to an urban search and rescue dog navigating rubble to find missing people. Egocentric vision research captures visual information, such as the objects present, from the first-person perspective of the participant. Egocentric vision research has become widely used to explore how human infants' visual environments change over the course of development, and how these changes impact, among other things, their developing recognition of faces and language acquisition. At present, however, egocentric vision research, and the resulting theoretical and applied advancements, have been limited to humans. The present research aims to explore the visual statistics of the environment of the domestic dog, a species closely related to humans by emotional bond, rather than genetics, and relied upon by humans in a variety of working roles and as companions. As a starting point to understanding how dogs perform their various complex tasks, we must understand what their physical environments look like, from their point of view.

Why Study What Dogs See?

Dogs are an interesting study species for cognitive research due to their unique evolutionary history with humans, resulting in an arguably exceptional understanding of human social cues relative to other species. More specifically, dogs outperform great apes at following human social-communicative cues like pointing without explicit training (Bräuer et al., 2006). Further, dogs do not follow points blindly, but selectively trust their human informants. For instance, dogs preferentially follow points from informants who were previously accurate (Pelgrim et al., 2021), who are knowledgeable about the location of hidden food (Maginnity & Grace, 2014) and who they are more familiar with (Cook et al., 2014). Outside of the social domain, dogs have been the focus of study for other cognitive abilities, with recent work exploring their understanding of basic physical principles like gravity (Tecwyn & Buchsbaum, 2019), solidity (Espinosa, Tecwyn & Buchsbaum, 2021), and more abstract cognitive abilities like relational concept learning (Byosiere et al., 2017). Egocentric vision research, and the relevant advances made in other species, provides a natural route to further our understanding of dogs reasoning abilities across social, physical, and causal domains.

There, is also a growing interest in how dogs visually interact with their world. Dogs have worse visual acuity and less sensitive color perception than humans. In contrast, dogs are more sensitive to flicker rates and they surpass human visual performance in dim lighting conditions (Byosiere et al., 2018). Dogs are relied upon to navigate the human built visual world in a variety of working settings (i.e., as guide dogs for the blind) yet very little is known about how they complete these tasks. Researchers using stationary, screen-based eye-tracking have begun exploring how dogs visually interact with their environment, finding that dogs can recognize photos of familiar human and conspecific individuals (Somppi et al., 2014) and that they respond differentially to humans faces expressing different emotions (Somppi et al., 2016, 2017). Dogs tend to direct their visual attention to living creatures in the foreground (vs. the background), a pattern also observed in chimpanzees and humans (Kano & Tomonaga, 2009; Törnqvist et al., 2020). Similarities have also been found in broader visual patterns like gaze asymmetry, (more specifically left gaze bias or the tendency to look more to the left side of an image, most commonly seen in faces) across rhesus monkeys, dogs, and humans (Guo et al., 2009). Screen-based eye-tracking studies have made important advances, however there are significant limitations, namely in the kinds of research questions they can ask, as real-world stimuli cannot be used. We also know

In J. Culbertson, A. Perfors, H. Rabagliati & V. Ramenzoni (Eds.), *Proceedings of the 44th Annual Conference of the Cognitive Science Society*.

comparatively little about dog's visual systems, and there are unresolved questions about how dogs perceive images on screens (Byosiere et al., 2018).

Head-Mounted Eye-Tracking

To achieve more naturalistic results, researchers have begun using head-mounted eye-trackers. These systems capture the wearer's first-person view of the world, as well as recording their eye-movements. This captures both the objects present in the environment and which of those objects the participant looked at. They can be worn in a variety of ways (i.e., caps, glasses, goggles) allowing for their use in exploring natural behaviors with head shapes ranging from peacocks to lemurs (Shepherd & Platt, 2006; Yorzinski et al., 2013), and more recently dogs (Pelgrim et al., 2022). Head-mounted eye-tracking has also been used to facilitate cross-species comparisons of visual behavior, such as by comparing how cats and humans coordinate eye and head movements (Einhäuser et al., 2009). The largest take-up of this method though has come from research on young infants.

Head-mounted eye-trackers have given us insight into how infants respond to their mother's voices (Franchak et al., 2011) and how infants and parents coordinate joint attention to objects (Yu & Smith, 2013). They have also been used to capture how visual attention changes over development. As children transition from crawling to walking, they move from looking at the floor in front of them while in motion to looking at walls, objects, and caregivers. This changes their frequency of looks to caregivers, because in order to look at their caregiver, crawlers have to stop and either sit or crane their heads, whereas walkers can stay in motion and look ahead (Kretch et al., 2014). An improved understanding of infant's visual experiences has informed theories on language acquisition, namely that a statistical learning framework can reasonably be applied to word learning because of the distribution of object frequencies in naturalistic scenes. As an example, the first nouns that children learn tend to be those objects most frequently present in their environments (e.g., spoon, bowl, Clerkin et al., 2017). In sum, the objects present in a child's environment provide a constraint on their learning and development. Capturing the types and distribution of objects in children's visual environments has informed our understanding of their development across cognitive and social domains (Jayaraman & Smith, 2020).

The present study seeks to describe and categorize both the visual information available to dogs in their daily environments, as well as characterize how they direct their attention within that space. We took an ecologically valid approach to understanding dogs' attention in their daily environment by having dogs walk with their owners in a normal fashion along a predetermined route. Our study had three major aims. First, we explored if certain objects were present more or less in dogs' views, providing us with an understanding of the objects available for dogs to look at, as well as capturing a coarse measure of interest, as dogs move their heads as well as their eyes to look at things they find interesting. Second, we evaluated if dogs looked consistently across exposures to object classes relative to their presence in the environment (i.e., if they looked at a person each time there was a person in their field of view, or if they rarely looked at people while people were in their field of view). We evaluated this using the relative proportion of time dogs fixated on the object, relative proportion here referring to the amount of time that dogs looked to an object relative to the amount of time that object was in their field of view. We particularly wanted to explore the social domain, namely if people were looked to consistently across exposure and if they were looked at more than other non-social objects. Our third aim was to look for any individual differences between dogs both in the objects in dogs' field of view which of those objects' dogs looked to. It is possible that dogs may differ in what objects they find visually interesting, which could result in differences both in the objects in their field of view (turning their head towards object classes they find compelling) and in which of those objects they looked at.

Methods

Participants

Participants were 4 dogs (Female = 3, Mean Age = 54.25 months) recruited for participation in a broader eye-tracking training program. Dogs breeds represented were 1 Australian Labradoodle, 2 Mixed Breeds, and 1 Labrador Retriever. An additional 2 dogs were excluded from data analysis due to camera displacement ($n = 1$) and a failure to walk normally in the goggles ($n = 1$). Dogs were chosen for suitability with the eye-tracking training program and owner willingness to complete the training. Prior to participation in this experiment, dogs were trained at home by their owners to wear the eye-tracking goggles, using commercially available dog goggles. Dogs were approved to begin participation if owners reported that they were comfortable walking and behaving normally at home and outdoors wearing training goggles for at least 10 minutes.

Procedure & Materials

Throughout sessions, dogs wore a custom developed head-mounted eye-tracker consisting of two cameras affixed to dog goggles (Positive Science, Inc.). One camera records the dog's right eye via an infrared eye-camera with an adjacent infrared emitting diode (hereafter the eye camera). The other camera (hereafter the scene camera) recorded the dogs' first-person perspective, recording a field of view of 101.55º horizontal and 73.60º vertical. Like head-mounted eye-tracking systems in other species (Franchak et al., 2011), this is smaller than the field of view of the dog eye, and it is possible that objects were not captured by the camera, however it is unlikely that this impacts the objects they chose to look at as they would move their head or eyes. Videos from both cameras were digitized at 29.96 frames per second. This apparatus is adapted from comparable models in other species and has been validated using alternative methods (Figure 1, Pelgrim et al., 2022). Dogs also wore a harness

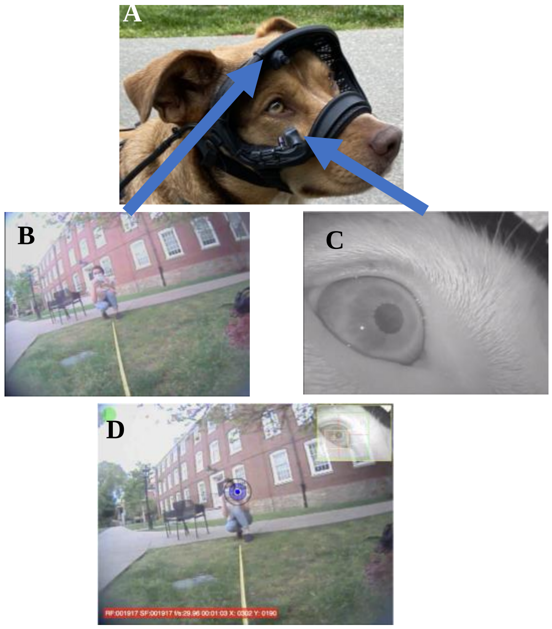

Figure 1**. A**. A dog wearing the eye-tracking goggles which had two cameras, **B.** The dog's view recorded by the scene camera, **C.** The dog's eye recorded from the eye camera. **D.** The dog's view with their point of regard indicated by the blue circle.

throughout their session which holds the video recording pack and its battery.

Prior to starting their walk, dogs first completed a calibration procedure. This procedure allowed for the dogs' eye movements as recorded from the eye camera to be mapped onto the field of view recording from the scene camera, the result being dogs' point of regard (or where in their environment they were looking), which could be extrapolated offline for the entire recording, after the session (Pelgrim et al., 2022). To complete this mapping, we use points where we know the dogs' point of regard (where they are looking). To accomplish this, the experimenter drew their attention to specific points using a treat. The dog owner held their dog's head stationary while the dog followed treats held by an experimenter, via eye-movements alone, through 5 unique points in space. Each point in space where the dog looked at the experimenter provided a known point, meaning that the positioning of the dogs' pupil and corneal reflection was linked to where in their first-person view they were looking. The 5 points were chosen to be spread widely across the dogs' first-person view, thus requiring a wide range of eye movements. These eye movements made the offline extrapolation of the point of regard for the entirety of the walk using eye-tracking software more accurate.

During the calibration procedure a removable handheld screen was plugged into the recording pack to allow the experimenter to verify the eye camera was recording a clear and centered image. After the dog looked at the experimenter in all 5 points, as judged by the experimenter, the LCD screen was removed. The calibration procedure was completed both before and after the walk, to provide enough known points for 1) a successful calibration and 2) verification of that calibration accuracy (more details in Data Coding & Analysis).

Following the first calibration, dogs walked with their owners, following the experimenter's directions, along a pre-set route. The route was 0.5 miles and was chosen for its variety of scenery, including both city streets and quiet campus greenspaces. Owners were instructed to walk their dog as normal, and the experimenter followed behind the dog-owner pair, recording the dog via a handheld camera. If at any point during the session the eye-tracker was disturbed or shifted (i.e., the dog shook their body or brushed against a wall), the fit was adjusted, and the eye-image was verified. In the event of tracking disruption, the calibration procedure was also repeated.

Data Coding & Analysis

After the session, video data recorded from the eye and scene cameras was combined as described above, using between 4 and 9 calibration points (Yarbus eye-tracking software, Positive Science Inc.). This process identified both the timing and the direction of dogs' fixations. Fixations were defined as a stable positioning of the eye lasting for 100 ms or more. More specifically, the timing (start and stop in ms) and the dog's point of regard in the visual scene (defined by x-y coordinates from the scene camera) was identified for each fixation.

This eye-tracking system has previously been established to have a spatial accuracy of approximately 2−4º in humans (Franchak et al., 2011; Watalingam et al., 2017) around 4º in peacocks (Yorzinski et al., 2013) and around 3.6º in dogs indoors (Pelgrim et al., 2022). The spatial accuracy of the eye camera mapping onto the scene for our outdoor walks was calculated, as in past work, using the unused points from the calibration procedure. The distance between the extrapolated point of regard (where the eye-tracking software calculated the dog to be looking) and the known point of regard (where the dog was known to actually be looking, namely at the treat bag in the experimenter's hand) was calculated for approximately 20 frames across the calibration points not used for the mapping, providing the spatial accuracy of the mapping, in degrees, for each dog. The spatial accuracy for the present sample was 5.4º. This is less precise than past implementations mentioned above, however it was to be expected given that this is the first time this system has been deployed outdoors under natural variable lighting conditions. Further, all the objects coded for are sufficiently large that the reduction did not have a significant impact on overall results

Objects in view, as well as which object the dog was looking at, were consistent across all frames for a given fixation. For each recorded fixation, what object the dog was looking at and what objects were present in the dog's field of view were manually recorded for a series of sixteen common objects observed in the world (see Table 1 and Figure 3). These objects were chosen ahead of data collection as they were consistently present on the pre-determined route. The primary focus of this study was how dogs interact with their world visually, so instances where dogs were relying on another sense (such as while sniffing) were removed. Sniffing bouts were defined as looks where two or fewer objects were present in the environment. As an example, when a dog was sniffing a pole, the only objects visible in the environment were the pole and the plant and both were so close to the camera it's unlikely that the dog was visually considering them (see Figure 2).

Figure 2**. Left** – Example of a sniffing bout on a plant (fixations where dogs had 2 or fewer objects present in their view) vs **Right** – Example of a normal fixation to a plant. Sniffing bouts were removed prior to analysis because the proximity of the objects of focus made it likely that they were using another sense, like olfaction.

Results & Discussion

Objects In View

Our first aim was to explore the objects present in dogs' view during their walks. Across dogs a total of 4,578 fixations were recorded spanning 49,431 frames. Each fixation was coded for both the classes of objects present (i.e., plant, sky, & pavement) and the object the dog was looking at (i.e., plant). After eliminating sniffing bouts, or those that contained 2 or fewer objects in the view as described in data coding and analysis, 4,352 looks remained and were used in subsequent calculations of proportions and analysis.

For all dogs, the four most common objects in their field of view were plants, pavement, buildings, and the sky (Table 1, Figure 3). These objects were nearly ubiquitous in dogs' environments, present between 99.7% (for plants) and 86.8% (for sky) of the total looks recorded. Poles, people, and cars were the next most frequent objects, occurring between 45.3% (for poles) to 30.1% (for cars). The only object from the list of 16 coded that was not observed was other dogs. No other dogs were encountered on these walks so this object category was dropped. Objects were also present in dogs view for different amounts of time. A linear regression exploring the time the object was in view as a function of the object identity found a significant main effect of object, $F(14) = 2.16$, $p = 0.028$.

The proportion of time that dogs looked to objects in their environment (relative to how often they were in the environment) was significantly correlated with the proportion of time those objects were in their field of view, $r(58) = 0.326$ $p = .01$. Dogs generally move their heads and eyes together towards objects that interest them, so we expected that data influenced by head movements (the objects in their view) and data created from eye-movements (fixations) would correlate. However, exploring where dogs are actually fixating provides a more nuanced understanding of what they are attending to and find visually interesting. Despite the two being highly correlated, there are some interesting differences in the proportion of time an object was in view and the relative proportion of time it was looked at.

Relative Time Looking to Objects

Our second aim was to explore, of the objects in their view, how and which of the objects did dogs choose to look at. First, dogs did not look uniformly at the objects present in their view (Table 1, Figure 3). We conducted a linear regression exploring object class as a predictor for the proportion of time looking to the object, relative to the duration it was in dogs' field of view for, and found a significant main effect, $F(14) = 2.87$, $p = 0.004$. This suggests that dogs are not uniformly or passively observing the objects in their field of view but are actively directing their attention to certain classes of objects, most notably people. People were the 6th most frequent occurrence in dogs' environment, occurring about 37.2% of the time in dog's views, yet they were the second most looked at object, relatively speaking (31.5% of the time there was a person in view, dogs looked at that person) (Figure 3).

Table 1: Objects Fixated on and In View

Object	Proportion In View (Rank)	Proportion fixated while in View (Rank)
plant	0.997 (1)	0.432 (1)
pavement	0.952 (2)	0.216 (3)
building	0.939 (3)	0.151 (5)
sky	0.868 (4)	0.016 (14)
pole	0.453 (5)	0.050 (12)
person	0.372 (6)	0.315 (2)
car	0.301 (7)	0.103 (7)
construction	0.060 (8)	0.134 (6)
bicycle	0.058 (9)	0.100 (8)
sign	0.055 (10)	0.095 (9)
chair	0.050 (11)	0.001 (15)
sculpture	0.031 (12)	0.186 (4)
bench	0.030 (13)	0.056 (11)
bus	0.013 (14)	0.061 (10)
scooter	0.011 (15)	0.031 (13)
dog	Not observed	Not observed

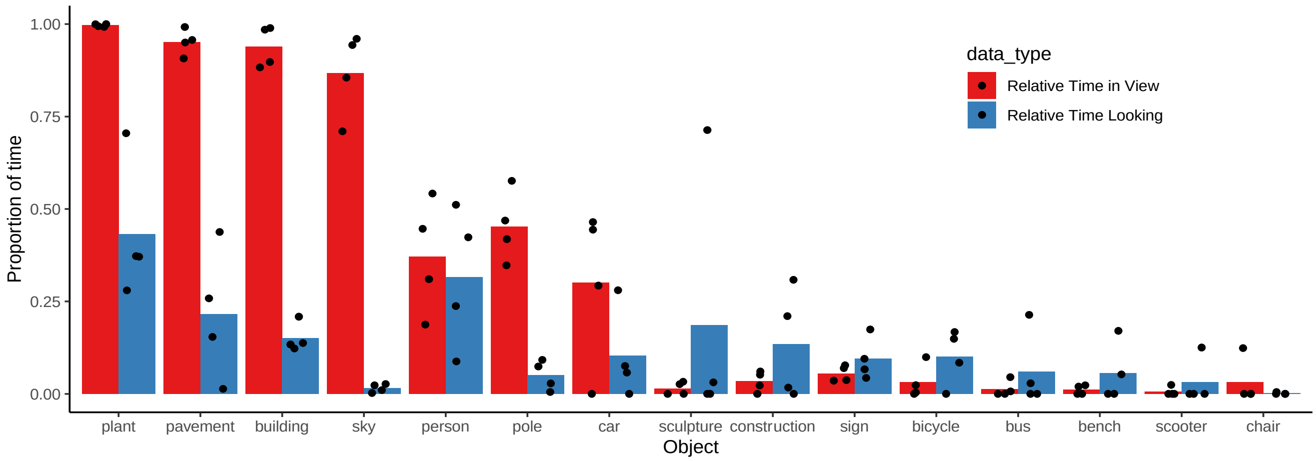

Figure 3. The proportion of the recorded walk that each of the objects were present in dogs' field of view (Red, Left) and the proportion of time dogs looked at that object relative to the amount of time it was in view (Blue, Right). Proportions from each dog are indicated by black dots. Dogs most often had plants, pavement, building, and sky in their field of view. Dogs looked, relatively speaking, mostly to plants and people.

Dogs preferential looking to humans is consistent with previous work examining dog's visual behaviors using screen-based eye-tracking (Törnqvist et al., 2020). Further, it supports previous research which has suggested that dog's excellent response to human social cues may be because they pay greater attention to humans (Mendes et al., 2021).

In addition to looking proportionally more to people when they were in their field of view, dogs also appeared to look for people in locations where they could potentially appear (See Figure 4). On 20% of looks to buildings, dogs looked either in the window of the building or at the entryway. This number is also likely an underestimation, as buildings filmed in the distance could not be classified due to limited camera resolution and spatial accuracy of the eye-tracking system. In addition to looks at doorways and windows of buildings, one dog encountered a stopped bus with open doors and, though no one was actually entering or exiting the bus, this dog looked to the open doors of that bus, the location where a person could potentially appear (Figure 4). While only anecdotal at this stage, this newly discovered gaze pattern has implications for future research into social tasks, namely as it further supports the idea that dogs pay disproportionate attention to humans, and search for them when they are not present. Further, tasks involving dog's natural navigation of their physical world may be impacted by this finding, it's possible that physical or structural elements of dog's environments are, due to their historic association with humans, social in nature.

Beyond the social domain, plants were both the most frequent object in dogs' field of view and their most frequently looked at object. In past screen-based eye-tracking research in dogs, plants have been used as the background material to explore how dogs look at the primary subject of the image, typically a person or animal present in the foreground (Törnqvist et al., 2020). In contrast, another frequent background object from screen-based eye-tracking, sky, was almost never actually looked at by dogs. The sky was nearly ubiquitous in dogs' view, present 86.8% (ranked 4/15) of the time yet dogs looked extremely infrequently to it, only looking at the sky 1.6% of the time it was in their view (ranked 14/15) (Figure 3). This suggests that unlike plants, in a real-world context the sky is treated by dogs as background, and not something that is worth attending to. A major advantage of head-mounted eye-tracking is the use of the real-world stimuli and mobile participant, and in this case, our results suggest that dogs may consider at least some plants to be objects, exploring them visually and through other sensory modalities (the majority of sniffing bouts that were removed included plants), however they do not appear to consider the sky as an object worth investigating. Further research is needed to make more nuanced conclusions about dog's response to plants and other potential background objects.

Dogs also looked unexpectedly more to certain rare and unusually shaped objects in their environment, namely construction equipment, and sculptures. Both of these asocial objects were rare in the dog's view, present in the field of view for 3.1% of looks for sculptures and 6% for construction equipment. Both were proportionally looked at very often (18.6% for sculpture, the 12th most frequent out of the 15 in view to 4th most relatively looked at of the 15) and 13.4% for construction, rank 8/15 to 6/15 respectively, see Table 1). This suggests a potential preference for novelty when considering which object to look at, and a greater interest in relatively novel or at the least unusual objects. This is in line with past research showing that dogs have a strong preference for novel objects on an object choice task (Kaulfuß & Mills, 2008). Future research may explore if this neophilia extends to other domains or could more explicitly compare novel objects by staging them along a walk or by presenting dogs with a forced-choice task between a familiar and novel object to see which they both physically and visually explore.

Figure 4. Dogs looked to specific components of objects like the doorways and windows of buildings, as well as the open doors of a bus, potentially looking to where they expect people may appear.

Individual Differences

No individual differences were observed in the proportion of item that objects were in dogs' view (Figure 3). Dogs generally had the coded objects in their view for comparable amounts of their walk time. We conducted a linear regression exploring duration in view as a function of object class and dog identity and found no significant effect of dog identity, $F(3) = 0.37$, $p = .775$. Given that dogs walked the same route, they had the opportunity to orient their fields of view towards many particular objects (e.g., buildings) for comparable amounts of time, however it is still notable that dogs' different sizes and training experiences did not result in them directing their heads differently on their walks.

We can also consider a more detailed measure of what dogs chose to look at within their field of view. When considering relative proportion of time that dogs looked at object classes, relative to the amount of time those objects were in their view there was some variability (Figure 3). As an example, Suna looked to people 50% of the time there was a person in her view, whereas Daisy looked to people around 10% of the time they were in her view. Despite some notable instances of differences, there was no statistically significant difference in relative proportion of looks to objects. A linear regression exploring dogs' relative proportion of time looking to objects as a function of object class and dog identity found no significant effect of dog, $F(3) = 1.266$, $p = .298$. While no individual differences were noted in this sample, dogs undoubtedly experience different views and objects as a function of where they live and a host of other lifestyle factors. More research is needed into individual differences between more dogs in alternative contexts.

Conclusion

The present study aimed to explore both the objects present in dogs' visual environments as well as which of those objects they chose to look at. We found that dogs looked more to plants and people, than to the other objects, and discovered that dogs also look to where humans may appear, such as doorways and entryways of and busses. Dogs looks to people supports prior research on dogs excellent understanding of human social cues, and provides quantitative support for the hypothesis that dogs extensively attend to people. We noticed here that dogs directed their attention to doors and windows. By examining the field of view for image features, we can determine if dogs look to doors and windows of buildings because they are the most salient features of buildings, or if they are truly looking there for social reasons due to their past associations with humans. Our findings on dogs looks to plants are in contrast with prior work where plants are generally considered to be background material. Further research is needed in an ecologically valid context like the one presented here to further explore what components of plant material dogs are so interested in. Further, we found suggestions of visual neophilia in dogs, with dogs looking more to unusual and rare objects including sculptures and construction equipment. Finally, we found that, on average, individual dogs were very similar in both the objects present in their view and which of those objects they chose to look at. However, detecting individual differences may require more dogs than our sample with a variety of breeds or more diverse life experiences.

This is the first effort to explore how dogs look at their physical environment. Future research can expand on the object classes identified here, and further explore the pattern noted here that dogs also look to where people may appear. One limitation of the present study was the spatial accuracy of the system, but with increased camera resolution or image enhancement, future work can identify whether, for instance, dogs look more to the door of cars than they do to the bumpers or tires (strictly non-social components). Future work can also consider conducting more detailed compositional analysis of what is in the dog's field of view. This could help to provide more context about the intentionality of looks (i.e., if for a given frame plants took up 95% of the scene, and a person was 5% yet the dog chose to look at the person). Future work can also explore dogs' reaction to rare or unusual objects, informing our understanding of dogs' visual neophilia, using a similar paradigm to stage encounters. Further, reactive dogs (those that have a strong arousal response to a given stimuli such as a dog or a person on a bicycle) would be promising candidates for use in this paradigm to understand how hey scan their environments and how they, temporally, respond to triggers.

This study was the first to record how dogs observe their physical environment in a naturalistic setting. Building upon this understanding, we can now expand into how dogs complete more complex social tasks. Very little is currently known about how, visually, dogs build a bond through play with a human companion or how they navigate a complex physical environment with social guidance, such as in dog agility. Understanding the visual behaviors that dogs are utilizing to complete daily tasks, and how those differ from key visual features seen in human-human interactions, will provide insight into social learning and cooperation in a unique cross-species context. Additionally, being able to measure how dogs visually interact with the world while completing tasks is a first step to building an eventual model of dogs' visual behaviors, something with significant implications for both working dog and AI training.

Acknowledgments

Thank you to our participants, their people, and the Brown Dog Lab team for their assistance in data collection.

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