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A cost-effective, simple measure of emotional response in the brain for use by behavioral biologists

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Background and aims: Studies combining brain activity measures with behavior have the potential to reveal more about animal cognition than either on their own. However, brain measure procedures in animal studies are often practically challenging and cost-prohibitive. Therefore, we test whether a simple measure of ear temperature can be used to index hemispheric brain activation using a handheld thermoscanner. Cortisol levels are correlated with the activation of the right cortical region, implying that, when stressful situations are experienced, increased right hemisphere activation occurs. This leads to corresponding locally detectable increases in ipsilateral ear temperature. *Methods:* We compared right- and left-ear temperatures of 32 domestic dogs under non-stressful and partially stressful conditions. *Results:* We detected significant elevations in right-ear temperature – but not left-ear temperature – relative to baseline readings in the partially stressful condition that were not detected in the non-stressful condition. *Discussion:* These findings provide encouraging support for the notion that tympanic membrane temperature readings can provide a simple index for canine hemispheric brain activation, which can be combined with data on behavioral decision-making, expectancy violations, or other measures of emotional processing. Devices are cheap, simple to use, portable, and only minimally invasive providing a means for real-time brain and behavior measurements to be conducted in real-world settings.

INTRODUCTION

Studies of animal cognition rarely adopt a dual approach combining behavioral inference and measures of brain activity. It seems obvious that studies combining even basic measures of brain activity with those of behavior have the potential to reveal more about animal cognition than either can on their own. There have been recent attempts to bridge the gap. Several studies have now used functional magnetic resonance imaging (fMRI) scanners to examine dogs, including Berns et al. (2015) who placed domestic dogs in fMRI scanners to measure brain activity while presenting subjects with scent stimuli. Such studies are delivering high-level sensitivity brain data. While this technology-based advancement is innovative and an exciting step forward in canine cognition research, such studies can be limiting for both practical and financial reasons. Furthermore, not all research will require high-level sensitivity of brain measures to answer a research question and studies may require subjects to be free moving and not restricted within lab environments. Methodologies combining brain and behavior investigation that are procedurally simple, low cost, and minimally invasive, as well as being ecologically valid, have the potential to broaden the scope of investigation.

Research on humans and other animals has shown external ear temperature (e.g., dogs: Riemer et al., 2016) and within-ear temperature to reflect hemispheric temperature in the brain with high accuracy (humans: Brinnel & Cabanac, 1989; Cabanac, 1993; Mariak et al., 1994, 2003; Ogawa, 1994; rabbits: Tanabe & Takaori, 1964; pig-tailed macaques: Baker et al., 1972; cats: Mazzotti & Boere, 2009). In humans, left and right hemispheres are responsible for processing different emotional responses (Ahern & Schwartz, 1985; Altenmüller et al., 2002; Davidson & Fox, 1982; Jones & Fox, 1992; MacNeilage et al., 2009; Turhan et al., 1998) and the same is true for several species of domesticated animals (dogs, cats, horses, chickens, and goldfish: Leliveld et al., 2013). Frontal and temporal lobe activity appears responsible for generating the corresponding side's hemispheric activity, which alters as a function of the motivational state experienced (Propper & Brunyé, 2013). While the left hemisphere processes positive emotional responses (non-stressful situations), the right hemisphere processes negative ones (Propper & Brunyé, 2013). Cortisol levels are known to correlate with activation of the right cortical region (Hewig et al., 2008; Kalin et al., 1998; Lee et al., 2015), implying that when stressful situations are experienced increased right hemisphere activation occurs. Thus, as the respective hemispheres of the brain controlling positive and negative responses are activated, in response to an individual experiencing emotion, right–left ear temperature differences are produced. Boyce et al. (1996) showed a strong correlation between tympanic membrane temperature (TMT) and stress response in both children and rhesus macaques.

For domestic dogs (*Canis familiaris*), previous research has demonstrated the same relationship between right hemisphere activation in the canine brain and observed responses and reactions to alarming and threatening stimuli (Siniscalchi et al., 2010), negative withdrawal emotions (Ahern & Schwartz, 1985; Davidson, 1992), aggression and fear (Casperd & Dunbar, 1996), and unexpected situations (Rogers, 2010). Additional evidence from individual case studies show ear temperature associated with the right hemisphere shifts in response to stressful situations (Lindsay, 2005).

In light of this, we ask "Is it possible to investigate these sorts of relationships and to test other brain and behavior theories using approaches that are less restrictive and more affordable than the existing protocols?" In this study, we test the applicability of a portable handheld thermoscanner to measure TMT to establish whether they can provide an index of ipsilateral hemispheric brain temperature. Our objective is to test the suitability of a handheld device that allows TMT to be used as a broad measure of emotional valence and hemispheric activation in the context of animal cognition and animal welfare studies. We therefore compare the right- and left-ear temperatures of domestic dogs in a non-stressful and a partially stressful condition using a handheld infrared thermoscanner. We predicted that dogs experiencing negative emotions when under stress would lead to detectable differential changes in right-ear temperatures relative to the left ear.

METHODS

Study subjects

Thirty-two domestic dogs, 14 males, 18 females, and their owners completed the study. The 33rd subject would not allow their owner to take their temperature and was therefore excluded from the study. Dogs ranged in age from 2 to 15 years. All dogs had lived with their owner for a minimum of 5 months prior to the start of the study. Demographic information is available in Supplementary Table S1.

Testing procedure

Experimental trials took place in dogs' own homes, so that they could be tested in familiar surroundings under conditions natural to them. Owners were present and involved in the trials. The testing procedure required the owner to call to their dog, replicating an everyday situation in which the dog was asked if it would like to receive a food treat. Dogs voluntarily took part in two trial conditions: a "successful" receive anticipated treat (RT) trial (i.e., a non-stressful condition) and an "unsuccessful" receive control (RC) trial (i.e., a partially stressful condition). Our control object was a pair of yellow-framed, black plastic sunglasses. Before the start of testing, we placed the control object where the dog's treats/food (goal object) was usually kept. This item was presented to the dog in the RC condition. There was a 10-min break between trial conditions, and condition order was counterbalanced across subjects.

In both trial conditions, the dog was called three times by the owner, in the way they would normally alert their dog and using their usual food-related phrase (e.g., "*Do you want a treat*?"). Immediately following the third call, the owner walked to the location of the reward. At the location, the owner collected either a treat or the control object. Then, they walked back to where they were seated when the trial began and presented the dog with the collected item.

Left- and right-ear temperatures were taken prior to commencing the trials, "baseline" reading, and immediately after each of the treat (RT) and control object (RC) conditions. We had owners take the ear temperature measurements to further reduce the potential for stress resulting from the dog being handled by a stranger. No stipulation was imposed on which ear was to be measured first.

Healthy dogs' normal TMT range is reported to be 36.8–38.8 °C (Hall & Carter, 2017). A Braun ThermoScan® 3 (IRT3030; Kronberg, Germany) was chosen for use as the aural device in this study, usually sold for use on human infants. We acknowledge that this thermometer does not take medically accurate readings nor is it a dog-specific device. However, our aim was to acquire readings that could sufficiently detect a difference between left- and right-ear temperatures.

Statistical analyses

In order to test whether the trial condition impacted upon the difference in ear temperatures, we first standardized the data for each dog by subtracting the "baseline" ear temperature for each ear from the recorded temperature under each trial (i.e., RT or RC object). We then estimated the difference in temperature between the right and left ears for each individual dog under each intervention. Finally, we created a linear mixed-effects model including the standardized temperature difference as the dependent variable, the trial condition as the independent variable, and the individual dog ID as a random effect. The model was created using the "lmer" package (Bates et al., 2015) in R version 3.5.2 (R Core Team, 2018), using the "lmerTest" package (Kuznetsova et al., 2017) to obtain p values. No intercept was included in the model in order to allow estimation of both trial conditions. We evaluated model assumptions using standard residual plots and estimated the model fit using a version of the R^2 measure adapted for use in mixed-effects models (Xu, 2003).

A Friedman's test was used in the analysis of the potential for random temperature change over time with no trial ("no trials" condition) performed in IBM SPSS 24.0 (SPSS Inc., Chicago, IL, USA).

RESULTS

Experimental trials

Individual dog ear temperatures, across all trials, are made available in Supplementary Table S2. Dogs' ear temperature ranged from 34.4 to 39.4 °C. Mean and standard deviation temperatures for baseline readings and the two trial conditions are presented in Table 1. Our assumption that there would be no difference between right- and left-ear temperatures, measured at baseline, was confirmed ($z = -1.333$, $n = 32$, $p = .182$).

The model fit, as assessed by generalized R^2 measure, was good ($R^2 = .9$). We found that, under the RC (i.e., partially stressed) condition, the right-ear temperature relative to baseline was around 1.0 °C higher than the left [95% confidence interval (CI): 0.2–1.8 °C], whereas under RT conditions, the right-ear temperature relative to baseline was around 0.8 °C lower than the left (95% CI: −0.0 to −1.6 °C) (Fig. 1). As indicated by the CIs, both of these estimates are statistically significantly different from the null hypothesis of no temperature change from baseline (Table 2).

Change over time: No trial condition

To mitigate against the possibility that the dogs' ear temperatures were simply changing over time and not a consequence of the trials' regime, separate measurements were taken using a sample of five of the dogs under a "no trials" condition. Three measurements of left- and right-ear temperatures were taken at three time intervals (T1, T2, and T3) to represent the trial condition intervals (Table 3). During the "no trials" condition, the dogs were left to interact with the individual(s) in the room as normal but without any trial conditions taking place.

A Friedman's test revealed no significant change in left- [$\chi^2_{(2)} = 0.125$, $p = .394$] or right-ear [$\chi^2_{(2)} = 4.000$, $p = .135$] temperatures across the three "no trial" intervals (T1, T2, and T3). Moreover, there was no significant difference between left- and right-ear temperatures in times T1, T2, and T3 [$\chi^2_{(1)} = 1.800$, $p = .180$].

DISCUSSION

The study demonstrates that TMT, detected through a handheld device, shows good potential to be an index for the effect of emotional valence on hemispheric brain activity

Table 1. Mean left and right TMT and standard deviation (*SD*) across all dogs ($n = 32$) by trial condition

Trial condition	Mean (°C) right TMT	*SD*	Mean (°C) left TMT	*SD*
Baseline	36.7	2.70	37.1	2.37
Receive treat (RT)	36.3	2.51	37.5	2.27
Receive control object (RC)	37.4	2.37	36.8	2.85

Note. TMT: tympanic membrane temperature.

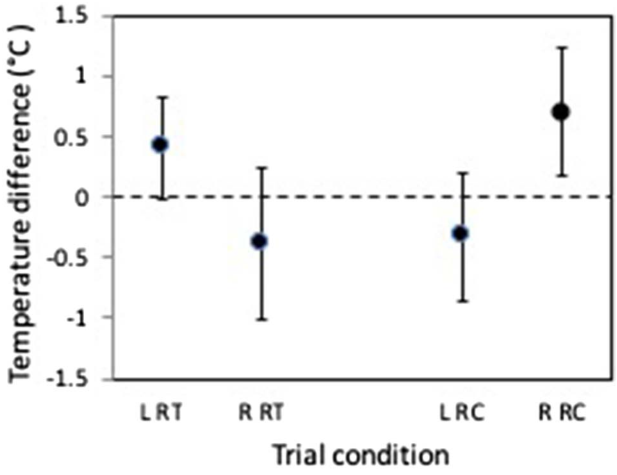

Fig. 1. Mean temperature difference from pretrial baseline values for left- and right-ear tympanic membrane temperature (TMT) in receive treat (RT) and receive control object (RC) conditions. Bars indicate 95% confidence intervals

in domestic dogs. Dogs learn that treats follow particular phrases and actions. When our subjects were instead presented with an alternative object (control), dogs' right-ear temperature readings increased more, on average, than the left ear; presumably as a consequence of an expectancy violation (see, e.g., Adachi et al., 2010; Albuquerque et al., 2016; Müller et al., 2011) that resulted in negative emotions being experienced. By contrast, when given the expected treat object, temperatures were, on average, higher than baseline in dogs' left ear but lower in the right ear. Emotional information is processed differently by the right- and left-brain hemispheres (Killgore & Yungelun-Todd, 2007) and, when dogs are subjected to different experimental conditions, their ear temperature reflects this. The thermoscanner used in this study was able to detect relative hemispheric differences under different trial conditions and relative to baseline readings. Further support of this assertion is the fact that, in a sample of five of the dogs, ear temperature did not change over time when measured in the absence of any trials being conducted.

The inference from these findings is that the trial conditions affected dogs' baseline (i.e., pretrial) ear temperatures as a result of those trials causing a hemispheric response under the influence of emotional valence. Elevated left TMT after receiving the anticipated treat object was a less anticipated finding but raises the possibility of this procedure also detecting positive emotional valences. Our observations are consistent with previous research that has suggested that the two hemispheres of the brain are responsible for processing differing emotional information (Schneider et al., 2013): the right hemisphere processing negative withdrawal-related emotions and the left hemisphere processing positive approach-related emotions (Ahern & Schwartz, 1985; Davidson, 1992).

Measuring TMT in dogs is simple. Thermoscanner devices are inexpensive; indeed, 1,000–10,000 times cheaper than other technologies in use (Helton et al., 2009b). They are safe to use, readily available, and highly portable, making possible the testing of subjects in settings outside of a laboratory. It is possible to test an animal's

Table 2. Generalized linear mixed model (GLMM) coefficient estimates

	Coefficient estimate	Standard error	*t* value	95% CIs	*p* value
RT standard temperature	−0.7937	0.4011	−1.979	−1.5871 to −0.0004	.0551
RC standard temperature	1.0312	0.4011	2.571	0.2379 to 1.8246	.0142

Note. Left ear is the reference. RC: receive control object; RT: receive treat; CI: confidence interval.

Table 3. Left- and right-ear temperatures of five dogs tested in the control condition over three time periods

Dog's ID	Time	Left ear (°C)	Right ear (°C)
Ma.Wor	T1	37.1	34.7
	T2	36.9	34.7
	T3	37.2	34.9
Pa.B	T1	38.1	35.9
	T2	38.2	36.9
	T3	38.1	35.9
Pu.S	T1	36.8	35.7
	T1	36.8	35.9
	T3	36.7	35.9
To.S	T1	35.2	35.3
	T2	35.2	34.6
	T3	35.4	35.7
St.W	T1	37.9	36.4
	T2	37.8	36.4
	T3	37.8	36.5

emotional valence processing while testing their behavior in real-world situations. The procedure is only minimally invasive and non-technical. Only one dog in this study had to be withdrawn due to not allowing his owner to measure his ear temperature. Such examples aside, this approach allows for largely unrestricted sample sizes. It further offers a novel approach to distinguishing between positive and negative emotional valences, with particular applicability to studies investigating welfare concern.

We acknowledge that this approach cannot substitute, provide as detailed information, nor be as comprehensive as electroencephalogram and magnetic resonance imaging procedures. Our readings are not medically accurate. Compared to human thermoscanners, dog-specific devices are differently shaped with the temperature probe extended and angled toward the dog's tympanic membrane. Greer et al. (2007) caution that human devices might read the temperature of the skin lining in the ear canal, if incorrectly inserted, rather than the tympanic membrane. However, while this would be problematic in veterinary examinations trying to establish the animal's core body temperature, this does not negate the findings in this case wherein we were attempting to establish if there were between-ear temperature differences. We did not validate the accuracy of our readings in this study. However, in the unlikely event of potential "errors" in reading here, they are likely to have affected left and right readings in equal measure. It is also noteworthy that when measured in the absence of any trials being conducted, ear temperature did not change over time. Nevertheless, pet-specific devices are recommended for future applications.

Questions still need to be answered about the precise nature of ear temperature and brain activity (Propper & Brunyé, 2013). Some researchers state that a *decrease* in ear temperature indicates increased hemispheric activity (Cherbuin & Brinkman, 2004; Dabbs, 1980; Helton et al., 2009a, 2009b; Hopkins & Fowler, 1998; Meiners & Dabbs, 1977) with others stating that warmer ear temperatures reflect cerebral activation (Boyce et al., 2002; Genovese et al., 2017; Gunnar & Donzella, 2004; Jackson, 2011; Laughlin et al., 1998; Mariak et al., 1994; Swift, 1991). Methodological differences may provide a partial explanation (see Propper & Brunyé, 2013 for a review of the human literature). The results conform to one of those statements but the exact nature of the relationship between ear temperature and hemispheric activation needs to be determined to remove confusion from the field. For our purposes, the TMT procedure detected relative differences, which met the requirement of this study.

For simple hemispheric comparisons, rather than detailed investigation of brain region activity, handheld thermoscanners provide a novel economically viable research tool for measuring TMT within animal cognition and animal welfare research. Naturally, the approach is restricted to easy to handle, compliant, domesticated and other animals; however, non-human primates, for example, have also been tested this way (e.g., Hanbury et al., 2012; Hopkins & Fowler, 1998; Parr & Hopkins, 2000; Tomaz et al., 2003) and hence the potential for wider application exists. For dogs, laboratories and other strange environments can induce a stress response in study subjects (Bekoff & Jamieson, 1991; Stewart et al., 2015), presenting a confounding variable to some study designs. The portability of thermoscanners means subjects can be tested under naturalistic conditions, increasing ecological validity while still collecting brain activity data in the field. While our focus has been around the application of use in emotional response studies, the potential to conduct cognition research more widely exists; for example, in decision-making contexts more broadly and where underlying cognitive mechanisms in tasks are known to emanate from one or the other brain hemisphere. Given its simplicity, it is surprising that the TMT approach has not already become more widespread among animal researchers as it has been adopted in neuropsychological studies of humans for some time. We encourage behavioral researchers to consider widening the use of proxies of (internal) mental states in conjunction with the data on (external) observable behavioral phenomena that they collect.

CONCLUSION FOR FUTURE BIOLOGY

Advances in our understanding of animal cognition, in the past 30 years, have been considerable. Future advances, however, will likely rely on technological advances because single discipline (i.e., behavior *or* brain) studies can reveal only so much about animal minds. Studies that are able to combine brain *and* behavior are likely to reveal more about animal cognition than either on its own. We demonstrate a simple, cost-effective, accessible, non-technical, and non-invasive method for collecting brain data, in real time using real-world settings, useful in animal behavior studies. Portable handheld thermoscanners measure within-ear TMT providing an accurate index of the ipsilateral hemispheric brain temperature. We tested this applicability using domestic dogs. Dogs received either the expected treat or were instead given a non-treat object (partially stressed condition). This study was able to detect left–right differences in ear temperature that corresponded to dogs' expected emotional state induced by the two trial conditions. Portable technology opens up the possibility of conducting animal research in natural environments with large sample sizes. Portable technology that can provide information about brain hemisphere activity can enhance and strengthen conclusions derived from behavioral observation data not only in animal decision-making studies but also animal welfare.

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Authors' Contributions: SJOH and HKW conceived of and designed the study and drafted the manuscript. HKW coordinated the study and carried out the data collection. SJOH carried out the statistical analysis. Both authors gave final approval of the manuscript for publication.

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