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5 What factors really influence domestic dogs' (*Canis familiaris*) search for an item dropped down
6 a diagonal tube? The tubes task revisited

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Abstract

It has been suggested that domestic dogs—like young human children—have a ‘gravity bias’; they expect an unsupported object to fall straight down, regardless of any obstacles that redirect or halt its path. In the diagonal tube task this bias is revealed by a persistent tendency to search the incorrect location directly beneath the top of the tube the item is dropped into, rather than the correct location attached to the bottom of the tube. We presented dogs (N=112) with seven different versions of the diagonal tube task, replicating and extending previous research, to examine what factors influence their search behavior for an object dropped down a diagonal tube, and investigate their physical reasoning skills more generally. Contrary to previous claims, we found no evidence for dogs exhibiting a persistent, or even a trial 1, gravity bias. However, in line with previous reports, dogs were also unable to search correctly for the reward, even when it could be heard rolling through the tube, though they succeeded when the tube was transparent (Exp. 1a-c). Exp. 2 suggested that dogs might search on the basis of proximity, but Exp. 3a-b ruled this out and showed that they prefer to commence searching at the center of the apparatus. Finally, when potential sources of bias were eliminated from the task (Exp. 4), dogs’ performance was improved, but still not above chance, suggesting that they are unable to reason about the tube’s physical-causal mechanism. We conclude that, on current evidence, the gravity bias might be unique to some primate species.

Keywords: comparative cognition; domestic dog; gravity bias; physical reasoning; tubes task

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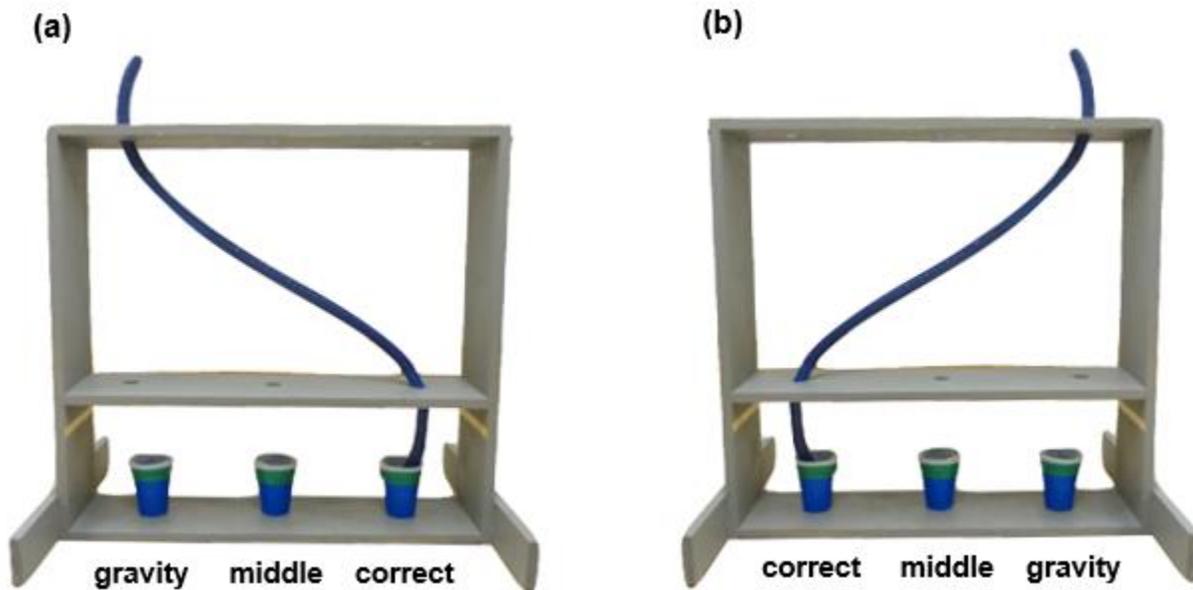
37 What factors really influence domestic dogs' (*Canis familiaris*) search for an item dropped down
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39 As human adults we possess sophisticated knowledge about the physical world. We know, for
40 example, that objects continue to exist even when they move out of sight; that a solid object
41 cannot pass through another solid object; and that gravity causes unsupported objects to fall (e.g.,
42 Baillargeon, 2002). Understanding how inanimate objects behave and interact with one another
43 is also important for young humans, as well as being ecologically relevant for many non-human
44 species. For example, it is extremely useful to be able to track and re-locate objects that move
45 out of sight, and all terrestrial species experience evidence of the effect of gravity on falling
46 objects, so it is feasible that similar physical reasoning mechanisms might be widely shared
47 among species. The developmental and evolutionary origins of our rich physical reasoning
48 abilities have thus long been of interest to researchers in the fields of cognitive development and
49 comparative cognition. Do young children and non-human animals (hereafter, animals) reason
50 about objects in the same way as human adults, or are there fundamental differences?

51 The tubes task (Hood, 1995) has been used widely in the fields of cognitive development
52 and comparative cognition to investigate children's and animals' physical reasoning abilities –
53 specifically, how different-aged children and different species reason about the way objects
54 behave under the influence of gravity (see Tecwyn & Buchsbaum, in press for a review). The
55 version of the task typically used with children consists of three intertwined opaque tubes
56 positioned vertically in a frame, each attached to a non-aligned cup at the base of the apparatus
57 (e.g., Baker, Gjersoe, Sibielska-Woch, Leslie, & Hood, 2011; Bascandziew & Harris, 2010;
58 Freeman, Hood, & Meehan, 2004; Hood, Wilson, & Dyson, 2006; Jaswal, 2010; Joh & Spivey,
59 2012). The task as typically used with animals is a simplified versions of this, and involves just a

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60 single diagonally-configured tube (Fig. 1). We will refer to this simplified version as the
61 'diagonal tube task', and given the comparative focus of the current study, the majority of this
62 introduction will focus on how individuals perform in this version of the task. Even in the
63 diagonal tube task that involves only one tube there are typically three possible search locations
64 at the bottom of the apparatus: the *correct* location connected to the bottom of the diagonal tube;
65 the *gravity* location, which is aligned directly beneath the release-point of the reward into the top
66 of the tube, and the *middle* location which is positioned between the other two locations (Fig. 1).
67 In accordance with the principles of gravity, solidity and containment, when dropped into the top
68 of the tube, the item travels (invisibly) down through the tube and ends up in the cup attached to
69 its bottom end. Participants typically first undergo some pre-training to introduce the different
70 search locations without the tube in place in the apparatus. The experimenter then puts the tube
71 in place and drops an item (typically a ball for children, a food reward for animals) down the
72 tube. The participant must then search for the item.



73

74 **Figure 1** Diagonal tube task apparatus showing the opaque tube in a top left-bottom right configuration (a)
75 and a top right-bottom left configuration (b). The gravity, middle and correct search locations are indicated
76 for each setup

77 While this is seemingly a straightforward task to solve, young children tend to perform
78 poorly. Interestingly, when instructed to search for the dropped item in the diagonal tube task, 2-
79 year-olds make a surprising, non-random error: rather than searching in the correct location
80 connected to the bottom of the single diagonal tube, they tend to search the gravity location (Fig.
81 1). Furthermore, they do not search the gravity location only in their first trial when they are
82 naïve to the task; they continue to do so across repeated trials, despite receiving feedback
83 regarding the correct location, which remains fixed across trials (number of 2-year-olds
84 searching gravity location in the diagonal tube task: trial 1: 9/10; trial 2: 8/10; trial 3: 9/10;
85 Experiment 4 pre-test, Hood, 1995).

86 According to Hood and colleagues (1995; 1998; 2006) “the gravity error is characterized
87 by repeated search in the box below despite adequate trials with feedback” (p. 304, Hood et al.,
88 2006). Specifically, young children’s perseverative searching of the gravity location
89 demonstrates resistance to counterevidence and suggests that they possess a naïve theory about
90 the influence of gravity on unsupported objects that is challenging to overcome. The search error
91 seems to be specific to objects moving under the influence of gravity, as children are less likely
92 to make a comparable error of searching the aligned location in a version of the task involving
93 upwards motion (Hood, 1998), or where the apparatus is horizontally configured (Hood, Santos,
94 & Fieselmann, 2000). This implies that children’s search error does not reflect a more general
95 straight trajectory bias, or a proximity bias, though it should be noted that a proximity bias has
96 never been directly ruled out in a vertical, gravity-based version of the tubes task.

97 It has been suggested that children develop a naïve theory about gravity during their first
98 year of life due to repeated exposure to objects falling straight down (e.g., Spelke, Breinlinger,
99 Macomber, & Jacobson, 1992). Given that this ‘straight down’ assumption is usually correct and

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100 therefore typically a useful heuristic to follow, this belief can be difficult to abandon (Hood et al.,
101 2006), and may therefore interfere with children's ability to succeed at tasks that require the
102 theory to be ignored (e.g., when an object is dropped down a diagonal tube). Further evidence
103 that this theory is resistant to counterevidence is the fact that even after young children
104 participate in a transparent version of the diagonal tube task—which they are able to pass—when
105 subsequently re-tested with the opaque version they revert to searching the gravity location
106 (Hood, 1995).

107 How is it that children are able to overcome their gravity bias at around 4 years of age?
108 Follow-up studies suggest that sufficient inhibitory control and causal knowledge are both
109 important factors. Dividing the attention of 4- to 5-year olds who would normally succeed with
110 the 3-intertwined-tube setup by dropping two balls simultaneously causes them to revert to a
111 gravity bias, suggesting that the bias persists but is typically suppressed by this age (Hood et al.,
112 2006). Modifying the apparatus to highlight the tube's physical-causal mechanism improves the
113 performance of children who would usually display a gravity bias (e.g. Bascandziev & Harris,
114 2011; Joh et al., 2011; Joh et al., 2012). Relatedly, even 2-year-olds do not show a gravity bias in
115 the table/shelf task (which would be revealed by reliable searching beneath the solid shelf; Hood
116 et al., 2000), where the physical-causal structure of the task is arguably much simpler than the
117 tubes task (no diversion of trajectory; no containment).

118 Several studies have explored how non-human species perform in the tubes task, with the
119 aim of discovering whether the gravity bias is unique to humans, or whether it is also seen in
120 other species, and could potentially represent an evolutionarily ancient naïve theory based on the
121 physics of life on earth (e.g. Hood, Hauser, Anderson, & Santos, 1999). Cotton-top tamarins
122 (*Sanguinus oedipus oedipus*) were the first non-human species to be tested, and the results of this

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123 study are the basis of claims that monkeys show a comparable gravity bias to young children.
124 While 7/9 individuals searched the gravity location in their first trial, the bias did not
125 compellingly persist across multiple trials – in trial 2, only 2/9 individuals searched the gravity
126 location (Hood et al., 1999), and so whether this meets the ‘challenging to overcome’ criterion of
127 a naïve theory is debatable. Three subjects succeeded at the task across 16 trials, and the errors
128 made by the other six subjects were distributed evenly between the gravity and middle locations.
129 Therefore, while this study provides evidence that tamarins’ initial search may have been
130 influenced by gravity, their behavior across trials does not bear the hallmarks of a naïve theory,
131 given that an initial bias was easily overcome by several individuals, and errors were as likely to
132 be directed at the middle location as the gravity location. Hood et al. (1999) also noted that
133 several tamarins developed a preference to search the middle location, which they suggested was
134 due to a lack of differentiation between the gravity and middle locations, both of which were in
135 closer proximity to where the reward was dropped from than the correct location.

136 In a separate study, cotton-top tamarins with prior experience of a horizontal version of
137 the diagonal tube task did not exhibit a gravity bias when subsequently tested with the standard
138 vertical version of the task (Hauser, Williams, Kralik, & Moskovitz, 2001), suggesting that any
139 gravity bias is not particularly robust in this species. As was the case for the tamarins tested by
140 Hood et al. (1999), Hauser and colleagues (2001) also noted that tamarins in both the vertical and
141 horizontal versions of their diagonal tube task developed a preference to search the middle
142 location, with the authors suggesting that this may have been due to them approximating the
143 position of the invisible food item.

144 Another callitrichid species—common marmosets (*Callithrix jacchus*)—did not exhibit a
145 gravity bias even in trial 1 when they were naïve to the diagonal tube task (4/7 individuals

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146 searched the gravity location, Cacchione & Burkart, 2012), but it is difficult to draw any firm
147 conclusions from this small sample of individuals. In their first block of 16 trials marmosets'
148 searches were randomly distributed between the three locations, but when they erred they were
149 significantly more likely to search the gravity location than the middle location (though this
150 difference disappeared in their second block of trials). Interestingly, when presented with a
151 looking-time version of the task, marmosets looked significantly longer when the reward was
152 revealed to have ended up in the gravity container than when it was revealed to have ended up in
153 the correct container. Thus, while they were not able to search correctly at above-chance level, it
154 is possible that they were implicitly aware of the role of the tube in constraining the reward's
155 movement (Cacchione & Burkart, 2012; see Lee & Kuhlmeier, 2013, for similar findings with
156 2-year-old children).

157 A study by Cacchione and Call (2010) presented all four species of non-human great ape
158 with the diagonal tube task, and found that they did not exhibit a gravity bias (only 8/22 subjects
159 searched the gravity location in trial 1) – in fact, they were able to locate the food item at above-
160 chance levels from their first trial (Cacchione & Call, 2010). However, analysis of the errors
161 made by the apes showed that they were significantly more likely to search the gravity location
162 than the middle location, suggesting that apes may indeed hold naïve beliefs about gravity, but
163 unlike 2-year-old children, they are usually able to suppress acting on the basis of this belief
164 when it is inappropriate (as in the case of the diagonal tube). The findings of an earlier study by
165 Tomonaga and colleagues (2007) fits with the idea that great apes might have a dormant gravity
166 bias. Their task used a different measure to the other studies described here (prediction before the
167 dropping event rather than search afterwards), and involved two crossed tubes rather than a
168 single diagonal tube. In this context, both juvenile and adult chimpanzees selected the gravity

169 option at above-chance levels, and a further experiment ruled out that their choices were based
170 on proximity. While the apparent presence of a gravity bias in this study versus the lack of a
171 reliable gravity bias in Cacchione and Call's (2010) task might be explained by the different
172 response measures used, it is also possible that apes are able to solve the single diagonal tube
173 task, but reveal a gravity bias when the task is more complex because more tubes are intertwined,
174 which is known to increase children's preference for the gravity location (Hood, 1995; Lee &
175 Kuhlmeier, 2013).

176 Taken together, these studies provide mixed evidence for the existence of a gravity bias in
177 non-human primates. Cotton-top tamarins showed a significant gravity bias in trial 1, but this did
178 not persist across trials and they were equally likely to search the gravity and middle locations
179 overall (Hood et al., 1999). Marmosets searched randomly initially, but were more likely to
180 search the gravity location when they made a mistake, at least in their first block of trials
181 (Cacchione & Burkhardt, 2012). Great apes were able to solve the single diagonal tube task, but
182 were more likely to search the gravity location than the middle location when they erred
183 (Cacchione & Call, 2010), and chimpanzees showed a gravity bias when they had to predict
184 where a reward would appear when it was dropped into one of two crossed tubes (Tomonaga et
185 al., 2007).

186 Only one study to date has investigated whether a non-primate species exhibits gravity-
187 biased search in the diagonal tube task. When domestic dogs (*Canis familiaris*) were presented
188 with the diagonal tube task by Osthaus and colleagues (2003), they searched the correct location
189 significantly less often than in a control task with a straight up and down tube (where the gravity
190 location and correct location were the same). In the diagonal tube task, 8/16 dogs searched the
191 gravity location in their first trial. Although dogs chose the gravity location more frequently than

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192 the two alternatives in trial 1, their performance did not differ significantly from random search
193 (two-tailed binomial test: 0.33 chance of searching gravity location; $p = 0.19$; not reported in the
194 original paper). The number of dogs searching the gravity location decreased rapidly across
195 trials, and in trial 16 only 2/16 dogs made a gravity error. Concurrently, the number of dogs
196 searching in the correct location increased across trials: from 3/16 in trial 1 to 10/16 in trial 16.
197 Across all trials several dogs searched in the middle location (5/16 in trial 1, and 4/16 in trial 16);
198 in fact, overall, more than 40% of searches were directed at the middle location. The authors
199 suggested that searching the middle might represent a strategy that dogs adopt when they are
200 uncertain about the reward's location. In a follow-up experiment where the middle location was
201 removed as a search option (Experiment 3, Osthaus et al., 2003), 6/8 dogs searched the gravity
202 location in their first trial, but they learned to search the correct location even more quickly than
203 they did in the experiment where the middle location was available as a search option.

204 Taken together, these data provide no evidence for a group-level gravity bias in dogs that
205 persists across trials (i.e., that could constitute a naïve theory of gravity), and suggestive but non-
206 significant evidence for a possible initial gravity bias present in trial 1. However, the authors
207 conclude that “Dogs, like toddlers and non-human primates, display a gravity bias”, though they
208 acknowledge that “dogs can learn to overcome this [gravity bias]” (p. 497, Osthaus et al., 2003).
209 Based on the findings of this single study, several authors have gone on to report that dogs
210 exhibit a persistent gravity bias (e.g. Bascandziev & Harris, 2011; Cacchione & Call, 2010; Joh
211 et al., 2011; Kunder, Reyes, Taglang, Baruch, & German, 2010; Range, Möslinger, & Virányi,
212 2012; Tomonaga, Imura, Mizuno, & Tanaka, 2007). However, having examined the data
213 presented in Osthaus et al. (2003), we do not believe there are grounds for such a strong

214 conclusion. It is therefore puzzling that the claim that dogs having a robust and persistent gravity
215 bias comparable to that of human toddlers is so pervasive in the literature.

216 Given that on existing evidence, whether and to what extent dogs exhibit gravity-biased
217 search in the diagonal tube task remains unclear, the first aim of the current study was to re-
218 examine dogs' performance in the diagonal tube task, to establish whether dogs, like young
219 children, show a gravity bias (Experiment 1a). An additional aim was to use the diagonal tube
220 task to investigate dogs' physical-causal reasoning abilities more generally, which remain
221 relatively understudied in comparison with their socio-cognitive skills, as well as in comparison
222 with the physical-causal reasoning abilities of other non-human taxa such as primates and
223 corvids. As a first step to address this deficit, we replicated previous diagonal tube task
224 experiments that have been conducted with apes (Cacchione & Call, 2010) to investigate how
225 auditory (Experiment 1b) and visual (Experiment 1c) information about the tube's causal
226 mechanism influences dogs' performance in the diagonal tube task.

227 Seeing as several dogs in Experiments 1a–c exhibited a tendency to search the middle
228 location, as was the case in Osthaus et al.'s (2003) previous study with dogs, in Experiment 2 we
229 replicated our Experiment 1a but with the middle location removed, to see how dogs' search
230 shifted when searching the middle location was no longer an option. This also provided a
231 replication of Osthaus et al.'s (2003) Experiment 3, but with a larger sample of dogs (16 vs. 8).
232 Based on the results of our Experiment 2, in Experiments 3a and 3b we probed whether dogs'
233 search might indeed be influenced by a gravity bias in some situations, or whether their behavior
234 might in fact be better explained by proximity between the reward's release point and the search
235 locations. These experiments represent novel versions of the diagonal tube task, as while the role
236 of proximity has been indirectly explored in comparisons of the vertical tubes task to the

237 horizontal tubes task (Hauser et al., 2001; Hood et al., 2000) and the version involving upwards
238 motion (Hood, 1998), to our knowledge it is the first time that the gravity location and most
239 proximal location to where the reward is dropped from have been de-confounded in a vertical
240 version of the single diagonal tube task in any species (though see Experiment 2 of Tomonaga et
241 al., 2007 for a test of the proximity bias in a two-tube version of the task).

242 Finally, in Experiment 4 we presented dogs with a version of the diagonal tube task
243 described in Gomez (2005) in which they could not search on the basis of any of the biases that
244 might have guided them in Experiments 1–3 (namely gravity, middle or proximity), to see
245 whether this would enable them to succeed, as would be predicted if they do understand the
246 causal mechanism of the tube, but are unable to inhibit searching on the basis of some bias.

247 Given that an important aspect of Hood's 'naïve theory' account of children's gravity bias
248 (e.g., Hood, 1995; 1998; Hood et al., 2006) is that the bias is resistant to counterevidence—that
249 is, it persists across repeated trials in spite of counterevidence—in all experiments we examined
250 both how dogs performed in trial 1, but also whether and how performance changed across
251 repeated trials. It is possible that dogs (and other animals) exhibit an initial gravity bias, but
252 unlike for young children this bias does not persist across trials. If this were the case then such a
253 bias would not be a candidate for a naïve theory of gravity, which would suggest that any bias is
254 qualitatively different from that shown by young children.

255 **General Methods**

256 **Subjects**

257 All test subjects were pet dogs whose owners volunteered to participate in the study. Dog
258 owners were recruited via email, local advertisements and local dog training facilities, and
259 subsequently completed a questionnaire. In order to participate, dogs could not have a prior
260 history of aggression towards humans and had to be in generally good health (including no

261 known issues with their vision or hearing). There were no breed or age restrictions, though all
262 dogs but one were at least 6 months old (see Table S1 for further subject details including breed).
263 Dogs participated either in the Canine Cognition Lab at the University of Toronto or in a similar
264 sized space at a dog training facility in the Toronto area. Each dog only participated in one of the
265 experiments.

266 **Materials**

267 The apparatus used was based on Hood's (1995) tubes task for children, and subsequent
268 tubes tasks adapted for use with animals (e.g., Cacchione & Call, 2010; Hood et al., 1999;
269 Osthaus et al., 2003, Fig. 1). It consisted of a wooden frame (height: 80 cm, width: 79 cm, depth
270 18.5 cm) with orthogonal 'feet' (length: 54.5 cm) for stability and a mid-section at a height of 29
271 cm to hold the bottom of the tube in place. There were three holes (3 cm diameter, 25.5 cm apart)
272 in the top of the frame and the mid-section above the cups that the tube could be passed through.
273 The possible search locations were opaque paper cups (height: 11 cm; diameter: 8 cm) that all
274 had inaccessible treats hidden in the bottom to control for odor cues and were padded with cotton
275 wool and soft fabric to mask the sound of treats dropping into them.

276 Our apparatus differed from that used by Osthaus et al. (2003), in that their search
277 locations at the bottom consisted of three adjacent boxes without any clear separation between
278 them. We reverted to a setup more similar to the original Hood (1995) apparatus as we felt that
279 the lack of clear physical separation between search locations may have been confusing for dogs,
280 and indeed it has been suggested that subjects' tendency to search the middle location in previous
281 studies may have been due to spatial confusion of the gravity and middle locations (Hood et al.,
282 1999).

283 Across all experiments a single tube (diameter: 2.75 cm) was positioned diagonally in the
284 apparatus. The start and end points of the diagonal tube within the frame—and hence the length
285 of the tube—varied between experiments, as did the number and position of the search locations
286 (see individual experiment sections and Fig. 2 and 4 for details). In all of the experiments except
287 for Experiment 1b a small piece (~ 1 cm³) of freeze-dried liver treat that moved inaudibly
288 through tube was used. To further eliminate any sound an electric fan was on in the room
289 throughout the testing session to provide white noise. The fan was on from when the dog entered
290 the testing space so they had time to become accustomed to the sound before starting the task. In
291 Experiment 1b a similarly sized but harder and heavier liver-based treat was used and the fan
292 was not turned on.

293 **Procedure**

294 **Warm-up.**

295 The aim of the warm-up was to ensure that dogs felt comfortable in the testing space, and
296 that they would interact with the cups to indicate their choice of search location during the
297 experiment. Upon arrival in the testing area, dogs were given approximately five minutes to
298 explore the space off-leash while the owner completed an informed consent form. After this
299 initial exploration period, dogs were introduced to the cups by the main experimenter, who
300 placed one cup on the ground, then showed the dog a treat and dropped it into the cup and
301 encouraged the dog to retrieve it by giving a release command (“OK!” unless the owner
302 suggested an alternative). Some dogs spontaneously knocked the cup over and retrieved the treat;
303 for dogs that touched the cup with their muzzle or paw but did not knock it over, the
304 experimenter tipped the treat out for the dog to eat. This was repeated until the dog
305 touched/knocked over the cup a total of three times. After this initial off-leash warm-up period,

306 dogs were put on leash and handled by a second experimenter (handler). Owners were present
307 during testing but were seated at the side of the room behind the dog's starting position (see Fig.
308 S1) and were asked not to interact with their dog during the experiment.

309 The study was approved by the University of Toronto's University Animal Care
310 Committee (UACC). All procedures were in accordance with Ontario's Animals for Research
311 Act, and the federal Canadian Council on Animal Care and complied with the APA Ethical
312 Standards for Use of Animals in Research. All sessions were video recorded.

313 **Cup pre-training trials.**

314 The aim of the cup pre-training trials was to introduce dogs to searching for treats in the
315 cups whilst they were positioned in the apparatus, and to both measure and reduce the influence
316 of any prior location biases during the test phase. The cups were in position in the bottom of the
317 apparatus (the number and location of cups varied between experiments, see individual
318 experiment sections and Fig. 2 and 4 for details) and the tube was not present.

319 The main experimenter knelt behind the apparatus and the handler held the dog on leash
320 in front of the apparatus at a distance of approximately 160 cm. The experimenter showed the
321 dog a treat, moved it back and forth above the frame mid-section to ensure the dog was tracking
322 it, then dropped it through one of the holes into the cup underneath (Fig. S2a, Video S1). The
323 experimenter then put her hands behind her back, stared at a fixed point on the wall behind the
324 dog, then gave a release command (e.g. "OK!") and the dog was allowed to search exhaustively
325 for the treat. A choice was defined as a dog making physical contact with a cup with their muzzle
326 or paw (sniffing a cup, staring at a cup or lying down in front of a cup did not constitute a
327 choice). As in the warm-up, once the dog had touched the cup the experimenter tipped the treat
328 out of the cup for the dog if necessary. Once a dog had chosen a cup it was removed by the

329 experimenter. This dropping of treats into cups was repeated in a pseudorandom order (with the
330 constraint that the treat was not dropped into the same location in more than two consecutive
331 trials) until the dog successfully located the treat on their initial search on six consecutive trials
332 (an equal number of times from each location). The individual cups were randomly interchanged
333 between trials so the same cup did not always appear in the same location.

334 Following Osthaus et al. (2003) we set the maximum number of cup pre-training trials to
335 30; however, if a dog showed a persistent location/side bias (defined as 12 consecutive searches
336 of the same location) we administered the following training: treats were no longer dropped into
337 the preferred cup, and pseudorandomly dropped into the other cups until dogs got 6 consecutive
338 trials correct; then we reverted to all 3 cups and they had to get another 6 in a row correct.

339 Therefore in a few cases the total number of trials including these training trials went above 30
340 (see individual experiment results for the range of pre-training trials required to reach criterion).

341 **Tube familiarization.**

342 The aim of the tube familiarization was to demonstrate the tube mechanism to the dogs.
343 While this step was not included in Osthaus et al.'s (2003) study, previous child studies (e.g.
344 Hood 1995) and some non-human primate studies (e.g. Cacchione & Burkhardt, 2012) have
345 incorporated this step. Given that dogs likely have little experience of items travelling through
346 hollow tubes it seemed an important step to include. The unconnected tube was held aloft so it
347 formed a loose S-shape, with the bottom end approximately at the dog's head height (see Fig.
348 S2b). The experimenter showed the dog a treat, then dropped it into the top of the tube so it
349 rolled out of the bottom of the tube and onto the ground, and the dog was allowed to retrieve it.
350 This was repeated until the dog spontaneously retrieved the treat (i.e. the experimenter did not
351 need to indicate the treat's location on the ground) on three consecutive occasions.

352 **Test trials.**

353 Each dog participated in 12 test trials presented in a single block immediately after the
354 tube familiarization. While Osthaus et al. (2003) presented dogs with 16 trials per condition,
355 pilot work suggested that the dogs in our study began to lose attention and/or become satiated
356 after around 12 trials (having already completed the cup pre-training and tube familiarization). In
357 line with previous studies with non-human animals, in all experiments dogs were randomly
358 assigned to one of two possible diagonal configurations of the tube, which were a mirror image
359 of one another (e.g. top left-bottom right, or top right-bottom left; Fig. 1). The experimenter
360 inserted the tube into the frame in full view of the dog and it remained in this position for all of
361 the test trials.

362 For each test trial the experimenter knelt behind the apparatus and the handler held the
363 dog on leash in front of the apparatus at a distance of approximately 160 cm. The experimenter
364 showed the dog a treat, moved it back and forth across the top of the frame until the dog tracked
365 it, then dropped it into the top of the tube, showed the dog her empty hand, placed her hands on
366 her lap, stared straight ahead at a fixed point behind the dog, then gave the dog a release
367 command (e.g., “OK!”) to search for the treat (see Video S2). The dog was allowed to search
368 exhaustively until they located the treat. We allowed exhaustive search to match previous studies
369 with dogs (Osthaus et al., 2003), apes (Cacchione & Call, 2009) and monkeys (Hood et al.,
370 1999). Pilot work also revealed that dogs quickly stopped participating (they refused to search) if
371 they were only allowed to search one location and chose incorrectly, which meant they were not
372 rewarded for that trial. While one might imagine that allowing exhaustive search reduces the
373 incentive for the subject to make an initial correct choice (because they ultimately get a reward
374 anyway), previous work has demonstrated that this is not the case for monkeys at least: in two

375 tubes task studies, performance did not differ according to whether subjects were allowed to
376 search exhaustively, or only allowed to search a single location and therefore went unrewarded if
377 they chose incorrectly (Hauser et al., 2001).

378 **Data coding & analysis.**

379 In both the cup pre-training trials and the test trials we scored the location that dogs
380 searched first. We coded searches as correct or incorrect. For the 3-cup versions of the task
381 (Experiments 1a-1c), if dogs searched incorrectly then their search was further coded as directed
382 at the middle or gravity location. To investigate performance in trial 1 of each experiment we
383 used Chi-square goodness of fit tests (3-cup versions) or binomial tests (2-cup versions) to see
384 whether the distribution of dogs' search differed from random. We used mixed effects logistic
385 regression models that assumed a fixed slope across subjects (including a random slope term did
386 not significantly improve fit for any experiment) to examine successful performance across all
387 trials in each individual experiment, and to look for change in performance over trials (lme4
388 package version 1.1.13; Bates, Maechler, Bolker, & Walker, 2015) in the R environment (Version
389 3.3.3; R Development Core Team, 2017). We used the same approach to examine the nature of
390 dogs' errors, and look for any change in the nature of errors made across trials. We also
391 compared overall performance in each experiment to chance. For the 3-cup versions of the task
392 (Experiments 1a-1c) we adjusted the intercept to account for testing against 0.33 (as opposed to
393 the standard 0.5 in the 2-cup versions) and used that to calculate an adjusted z statistic and obtain
394 the correct p -value. We used binomial tests to examine the performance of individual dogs. For
395 all 3-cup versions (Exp. 1a-1c), where we were interested in seeing whether individuals dogs
396 either searched correctly, in the middle, or at the gravity location significantly more often than
397 expected by chance we used a Bonferroni correction for multiple comparisons, so for these tests

398 alpha was 0.017 (0.05/3). Finally, mixed effects logistic regression models were also used to
399 compare performance between-subjects across all 3-cup versions (Exp. 1a-1c) and all 2-cup
400 versions (Exp. 2-4) of the task. As for the individual experiment analyses, we assumed a fixed
401 slope across subjects because including a random slope term did not significantly improve fit for
402 either comparison. All tests were two-tailed and alpha was 0.05.

403 A second coder scored the test trials of a randomly selected six dogs per experiment from
404 video footage to assess inter-observer reliability. Cohen's kappa for which location the subject
405 searched first on each trial was 0.98 (excellent agreement between coders).

406 **Experiment 1: Replicating previous versions of diagonal tube task**

407 **Experiment 1a: The classic diagonal tube task**

408 In Experiment 1a, we presented dogs with the classic version of the diagonal tube task
409 used in comparative studies, where a reward is dropped down an opaque diagonal tube, and
410 travels invisibly and inaudibly through it into the cup at its bottom end. In this version, no direct
411 perceptual information (either visual or auditory) regarding the reward's location is available
412 after it disappears into the top of the tube (Cacchione & Burkart, 2012; Hood et al., 1999;
413 Osthaus et al., 2003). The aim was to generate additional data to address the widespread claim in
414 the literature that dogs share a naïve theory of gravity with young children, despite limited
415 empirical evidence to support this.

416 **Subjects**

417 Sixteen dogs (4 male, 12 female; mean age = 66 ± 10 months) participated in Experiment
418 1a (Table S1). Three additional dogs were tested but excluded because they did not reach
419 criterion in the cup pre-training trials (1), or because they failed to complete the test trials (2).

420 **Materials**

421 The tube was opaque and configured top left to bottom right or top right to bottom left
422 (Fig. 1 and 2a). Freeze-dried liver treats were used for the test trials.

423 **Results**

424 On average, dogs required 12.2 ± 2.3 trials (mean \pm SEM; range = 6 – 44; median = 9.5)
425 to reach criterion in the cup pre-training trials. In their first test trial dogs did not show a bias to
426 search any particular location (chance: $16/3 = 5.33$ dogs searching correctly; $\chi^2 = 2.38$, $df = 2$, p
427 = 0.304); rather, they searched randomly for a treat that travelled invisibly and inaudibly down a
428 diagonal tube. Half of the dogs (8/16) searched the middle location, five searched the gravity
429 location, and three searched the correct location (Fig. 2a). Therefore, we found no evidence that
430 dogs' search behavior was guided by gravity when they were naïve to the task.

431 Across the 12 test trials, 52% of searches were directed to the middle location (mean_{middle}
432 = 6.2 ± 0.7 trials), 32% of searches were directed to the correct location (mean_{correct} = 3.8 ± 0.7
433 trials), and just 16% of searches were directed to the gravity location (mean_{gravity} = 2.1 ± 0.6
434 trials; Fig. 3a). A mixed effects logistic regression model revealed that, as a group, dogs'
435 tendency to search the correct location did not differ significantly from the 33% expected by
436 chance ($z = 0.61$, $p = 0.54$).

437 The mixed effects logistic regression model revealed a significant improvement in
438 performance across trials (Fig. 2a and Fig. 3b; trial log odds = 0.17, $z = 3.192$, $p = 0.001$, Table
439 S2). We ran a separate mixed effects logistic regression model to examine the search errors that
440 dogs made, which revealed that, across the 12 test trials, on trials where dogs erred they were
441 significantly more likely to search the middle location than the gravity location ($z = 3.71$, $p <$

442 0.001; Fig. 3a). Across trials, the number of gravity searches decreased significantly relative to
443 the number of middle searches (trial log odds = -0.16, $z = -2.27$, $p = 0.022$; Fig. 2a).

444 We also examined individual performance, and whether individual dogs had a preference
445 for any of the search locations. After correcting for multiple comparisons (Bonferroni correction;
446 $\alpha = 0.017$; a dog had to search the same location in at least 9/12 trials to produce a p -value <
447 0.017 in a binomial test) only 1/16 dogs searched correctly significantly more often than
448 expected by chance across the 12 test trials (10/12 trials correct; $p < 0.001$). Two out of 16 dogs
449 had a significant middle-location preference (10/12 – 11/12 trials; $p < 0.001$) and no dogs
450 exhibited a significant preference for searching the gravity location (maximum number of gravity
451 searches = 8/12, Table S3).

452 Discussion

453 When no perceptual cues were available, like children (Hood, 1995), monkeys (Hood et
454 al., 1999; Hauser et al., 2001) and dogs (Osthaus et al., 2003) tested previously, dogs as a group
455 failed to locate a reward dropped down a diagonal tube, either in trial 1 or across 12 trials.
456 However, there was no evidence that they searched on the basis of a gravity bias—when dogs
457 erred, they were significantly more likely to search the middle location than the gravity location.
458 In this respect their performance differed from that of tamarins, who exhibited a trial 1 gravity
459 bias (Hood et al., 1999), and children, who seemed to show a gravity bias that was difficult to
460 overcome, even after several repeated trials (Hood, 1995). The performance of dogs in the
461 current experiment also differed from that of great apes, who were able successfully locate the
462 reward at above chance levels within 9 trials (Cacchione & Call, 2010). Apes have previously
463 demonstrated superior physical-causal reasoning skills compared with dogs (Bräuer, Kaminski,
464 Riedel, Call, & Tomasello, 2006), so it is possible that they were better able to understand the

465 role of the tube in constraining the path of the reward. In the following two experiments we
466 explored whether highlighting the tube's physical-causal mechanism by making the reward's
467 passage through the tube audible (Experiment 1b) or visible (Experiment 1c) would improve
468 dogs' performance in the diagonal tube task.

469 **Experiment 1b: Auditory cues available**

470 In Experiment 1b we investigated whether being able to hear the reward travelling
471 through the tube (but still not hear it landing in the cup) would enable dogs to perform better in
472 the task, either because they could acoustically track the reward travelling through the tube, or
473 because the sound provided some information regarding the tube's causal mechanism. Great apes
474 tested with a comparable version searched randomly in their first trial, but were able to
475 successfully locate the reward at above chance levels within their first block of nine trials
476 (Cacchione & Call, 2010). Dogs have not previously been presented with this version of the
477 diagonal tube task.

478 **Subjects**

479 Sixteen dogs (10 male, 6 female; mean age = 42 ± 9 months) participated in Experiment
480 1b (Table S1). Three additional dogs were tested but excluded because they did not complete the
481 cup pre-training trials (1), or because their choice of search location was unclear in the test trials
482 (2).

483 **Materials**

484 The tube was opaque and positioned from top left to bottom right, or top right to bottom
485 left (Fig. 2b). A hard, heavier liver-based treat that made a rattling noise as it rolled down the
486 tube was used as the food reward and the electric fan was turned off.

487 **Results**

488 On average, dogs required 12.9 ± 2.6 trials (mean \pm SEM; range = 6 – 35; median = 6) to
489 reach criterion in the cup pre-training trials. In the first test trial, dogs did not show a bias for
490 searching any particular location ($\chi^2 = 0.88$, $df = 2$, $p = 0.644$; middle: 7/16; gravity: 5/16;
491 correct: 4/16; Fig. 2b).

492 Across the 12 test trials, 42% of searches were directed to the middle location (mean_{middle}
493 = 5.0 ± 0.8 trials), 36% of searches were directed to the correct location (mean_{correct} = 4.4 ± 0.1
494 trials), and just 22% of searches to the gravity location (mean_{gravity} = 2.6 ± 0.6 trials; Fig. 3b).
495 The mixed effects logistic regression model revealed that, as a group, dogs' tendency to search
496 the correct location did not differ from the 33% expected by chance ($z = -0.41$, $p = 0.68$; Fig. 3a).
497 However, their performance improved significantly across trials (trial log odds = 0.21, $z = 3.60$, p
498 < 0.001 ; Fig. 2b; Fig. 3b; Table S2). Examining the search errors that dogs made revealed that, as
499 in Experiment 1a, dogs were significantly more likely to search the middle location than the
500 gravity location ($z = 2.42$, $p = 0.015$; Fig. 3a). Across trials, the number of gravity searches
501 relative to the number of middle searches did not change significantly (trial log odds = -0.03, $z =$
502 -0.48, $p = 0.632$; Fig. 2b).

503 We also examined individual performance, and whether individual dogs had a preference
504 for any of the search locations. After correcting for multiple comparisons (Bonferroni correction;
505 $\alpha = 0.017$; a dog had to search the same location in at least 9/12 trials to produce a p -value $<$
506 0.017 in a binomial test) four dogs searched correctly significantly more often than expected by
507 chance across twelve trials (9/12 – 11/12 trials correct; $p < 0.012$, see Table S4 for apparatus
508 configuration information for these dogs). Two dogs showed a significant middle-location
509 preference (11/12 – 12/12 trials; $p < 0.001$) and as in Experiment 1a, no individual dogs

510 exhibited a significant gravity location preference (maximum number of gravity searches = 7/12,
511 Table S3).

512 **Discussion**

513 When acoustic cues were available, dogs still failed to locate the reward at above chance-
514 level, either in trial 1 or across 12 trials. Great apes tested previously with an acoustic diagonal
515 tube task searched randomly in trial 1 like dogs in the present experiment, but unlike dogs, apes
516 performed above chance across a 9-trial session (Cacchione & Call, 2010). Apparently, apes
517 were more able than dogs to utilize the sound cue, either by tracking the reward's movement
518 through the tube to the correct location, or because the sound highlighted the tube's causal
519 mechanism. This fits with previous research suggesting that, compared to other species, dogs are
520 relatively poor at using physical-causal cues to locate food (apes: Brauer et al., 2006; wolves:
521 Lampe et al., 2017).

522 **Experiment 1c: Transparent tube**

523 Hood (1995) found that if the tube was translucent so that it was possible to observe the
524 movement of the object dropped down it, then 2.5-year-old children were able to successfully
525 locate the item. In Experiment 1c we investigated whether dogs—who have not previously been
526 tested with a transparent version of the diagonal tubes task—would be able to solve the diagonal
527 tube task if they were able to *see* the reward moving through the tube, i.e. when the reward was
528 *visibly* displaced by gravity and constrained by the tube. This is important because if dogs do not
529 succeed in this version of the task, this might suggest that there are other task demands limiting
530 their performance. For example, an inability to search correctly in a transparent version could be
531 due to lack of motivation, some physical constraint of the apparatus (e.g., dogs avoid searching
532 the cup with the tube attached because it is harder to access), or an object permanence/working

533 memory failure, such that once the object is out of sight dogs are completely unable to reason
534 about its location (though success in the cup pre-training trials makes this unlikely).

535 **Subjects**

536 Sixteen dogs (9 male, 7 female; mean age = 67 ± 9 months) participated in Experiment 1c
537 (Table S1). Five additional dogs were tested but excluded because they did not reach criterion in
538 the cup pre-training (2), they did not complete the cup pre-training trials (1), they did not
539 complete the test trials (1) or because their choice of search location was unclear in the test trials
540 (1).

541 **Materials**

542 The tube was transparent so the reward could be seen sliding through it and was
543 positioned either top left-bottom right, or top right-bottom left (Fig. 2c). As in Experiment 1a, the
544 light freeze-dried liver treats were used and the electric fan was switched on to mask any residual
545 sound.

546 **Results**

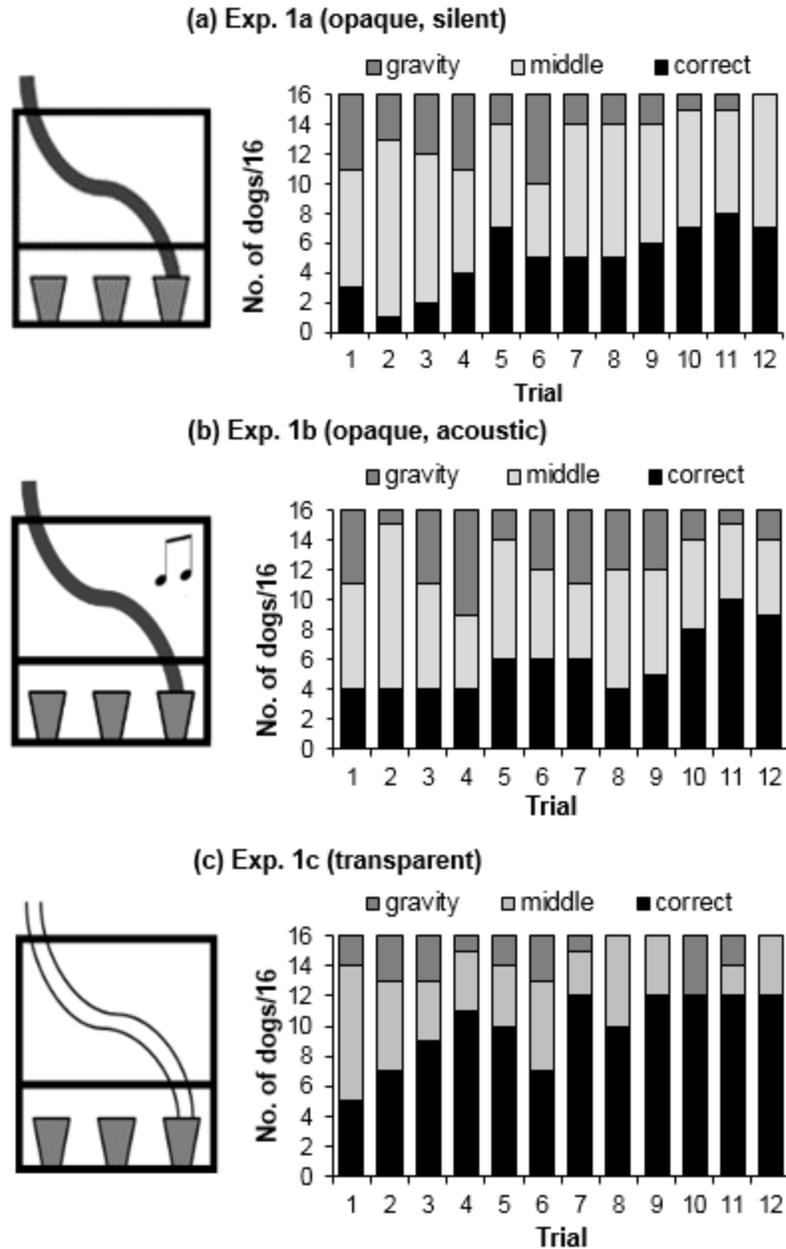
547 On average, dogs required 10.4 ± 1.1 trials (mean \pm SEM; range = 6 – 19; median = 9.5)
548 to reach criterion in the cup pre-training trials. As in Experiments 1a and 1b, dogs did not show a
549 bias for searching any particular location in their first trial ($\chi^2 = 4.63$, $df = 2$, $p = 0.099$), though
550 again, more dogs searched the middle location (9/16) than the gravity location (2/16) or the
551 correct location (5/16).

552 Across the 12 test trials, 58% of searches were directed to the correct location (mean_{correct}
553 = 7.0 ± 0.8 trials), 28% of searches were directed to the middle location (mean_{middle} = 3.4 ± 0.7
554 trials), and just 14% of searches to the gravity location (mean_{gravity} = 1.6 ± 0.4 trials; Fig. 2a). A
555 mixed effects logistic regression model revealed that, as a group, dogs searched the correct

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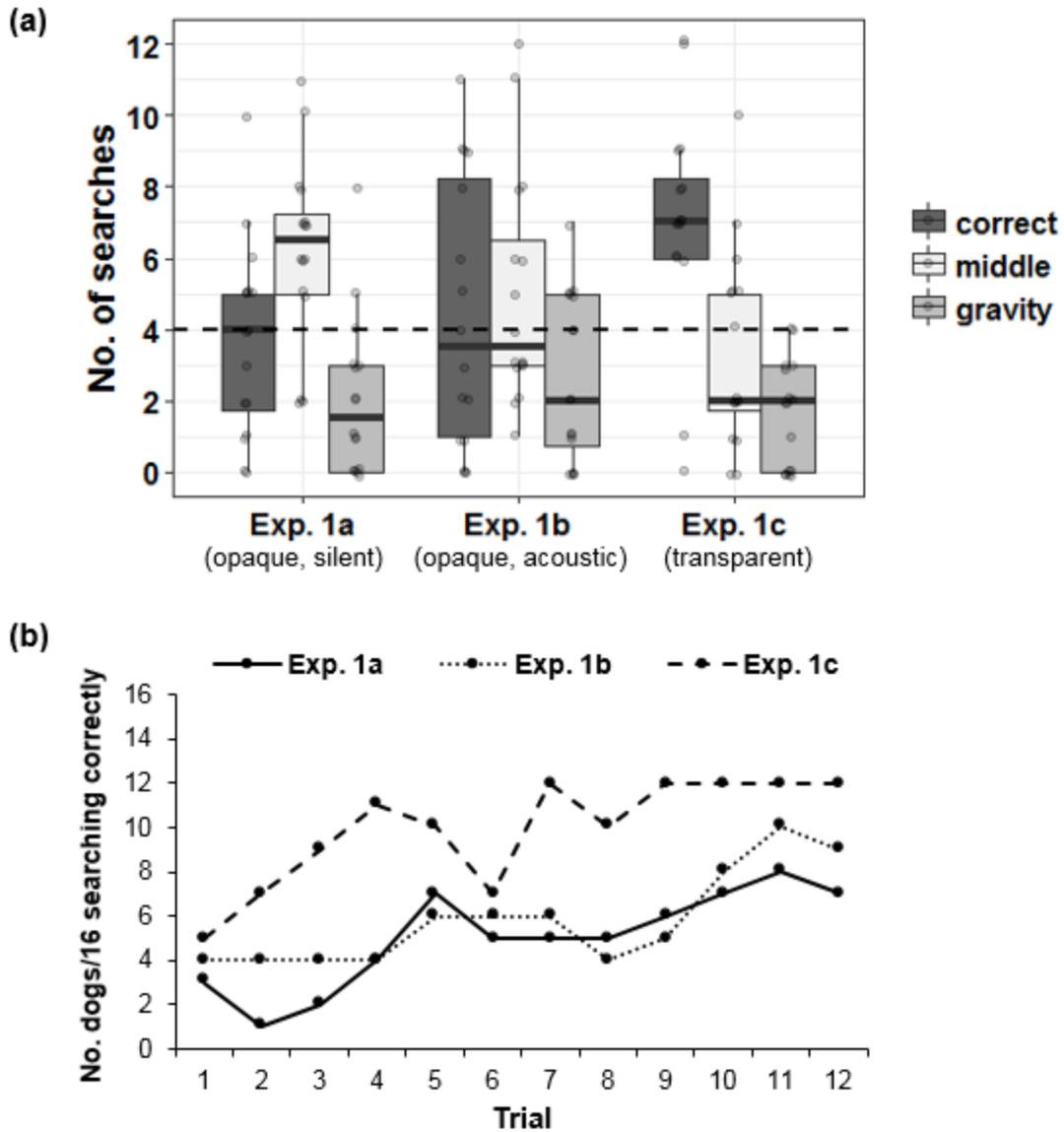
556 location more often than the 33% expected by chance ($z = 3.14, p = 0.002$; Fig. 2a). The mixed
557 effects logistic regression model revealed a significant effect of trial on performance (log odds =
558 0.18; $z = 3.59, p < 0.001$), so, as in Experiments 1a and 1b, dogs were more likely to search
559 correctly across trials (Fig. 2c and Fig. 3b; Table S2). When dogs made search errors, as in
560 Experiments 1a and 1b, they were more likely to be directed to the middle location than the
561 gravity location ($z = 2.245, p = 0.025$; Fig. 3a). Across trials, the number of gravity searches
562 decreased relative to the number of middle searches, but not significantly so (trial log odds = -
563 0.11, $z = -1.73, p = 0.08$; Fig. 2c).

564 We also examined individual performance, and whether individual dogs had a preference
565 for any of the search locations. After correcting for multiple comparisons (Bonferroni correction;
566 $\alpha = 0.017$; a dog had to search the same location in at least 9 trials to produce a p -value < 0.017
567 in a binomial test), 4/16 dogs searched correctly significantly more often than expected by
568 chance across twelve trials (9/12 - 12/12 trials correct; $p < 0.012$, see Table S4 for apparatus
569 configuration information for these dogs); 1/16 dogs had a significant middle-location preference
570 (10/12 trials; $p < 0.001$) and no dogs exhibited a significant gravity location preference
571 (maximum number of gravity searches = 4/12, Table S3).



572

573 **Figure 2.** Schematic representation of the configuration of the apparatus and the number of dogs searching
 574 each location across trials 1-12 in Experiments 1a-c where there were always three search locations. Black
 575 indicates correct cup; light-grey indicates middle cup; mid-grey indicates gravity cup
 576



577

578 **Figure 3.** (a) Box plot showing the distribution of dogs' searches of the correct, middle and gravity locations
 579 in Experiments 1a (opaque, silent), 1b (opaque, acoustic) and 1c (transparent, silent). The dashed horizontal
 580 line represents the expected number of searches per location if search was random. (b) Comparison of the
 581 number of dogs out of 16 that searched the correct location in each trial in Experiments 1a, 1b and 1c
 582

583 **Discussion**

584 When the displacement of the reward through the tube was visible, dogs, like 2-year-old
 585 children (Hood 1995) tended to succeed at searching correctly for it across the 12 test trials
 586 (though dogs did still make errors, especially in early trials). Like dogs, cotton-top tamarins that

587 participated in a transparent tube version of the task searched randomly in trial 1, but only 2/5
588 tamarins performed above chance across 10 trials (Hauser et al., 2001). Importantly, Exp. 1c
589 shows that solving the diagonal tube task is within the capabilities of dogs if they have sufficient
590 perceptual information, i.e., poor performance in opaque versions is not due to a lack of
591 motivation, physical constraints imposed by the apparatus, or a working memory/object
592 permanence failure.

593 **Comparison of performance in Experiments 1a – 1c and interim discussion**

594 Across Experiments 1a–c, dogs were presented with a situation where a treat was
595 dropped down a diagonal tube, and there were three possible search locations at the bottom of
596 the apparatus corresponding to correct, middle and gravity locations. As well as replicating
597 Osthaus et al's (2003) study with dogs (Experiment 1a), we manipulated the availability of
598 auditory (Experiment 1b) and visual (Experiment 1c) information to dogs, and have thus
599 replicated previous studies with non-human primates (Cacchione & Call, 2010) and human
600 children (Hood, 1995), to facilitate comparison of performance between species in the diagonal
601 tube task.

602 Mixed effects logistic regression that assumed a fixed slope across subjects was used to
603 compare dogs' ability to search correctly between Experiments 1a, 1b and 1c (Table S5). Dogs
604 were significantly more likely to search the correct location when the tube was transparent (Exp.
605 1c), compared with when no perceptual cues were available (log odds = 1.47, $z = 2.52$, $p =$
606 0.012), as well as when only acoustic cues were available (log odds = 1.31, $z = 2.23$, $p = 0.026$;
607 Fig. 3b). Performance did not differ between Exp. 1a and Exp. 1b (log odds = 0.16, $z = 0.27$, $p =$
608 0.790; Fig. 3b). Thus, being able to see the reward's trajectory helps dogs to identify its end
609 location, but being able to hear it travelling through the tube does not.

610 We found no evidence for a gravity bias in Experiment 1a–1c; the gravity location was
611 the least-searched option in all three experiments. This was true whether we considered
612 performance in trial 1, across all 12 trials, or at an individual level. On the basis of these findings
613 (and indeed the results of Osthaus et al.'s (2003) Experiment 1 diagonal tube condition) we
614 conclude that, contrary to previous claims in the literature, dogs' search behavior is not primarily
615 guided by a gravity bias in the diagonal tube task.

616 In Experiments 1a and 1b the middle cup was the most searched location and several
617 individual dogs showed a significant middle-bias. Even in Experiment 1c where dogs succeeded
618 at locating the reward overall, the middle was the second most common choice across trials. This
619 preference for commencing searching in the middle was noted of the dogs in the diagonal tube
620 condition of Osthaus et al.'s (2003) Experiment 1, and has also been recorded for some cotton-
621 top tamarins (Hauser et al., 2001; Hood et al., 1999) and common marmosets (Cacchione &
622 Burkhardt, 2012). It has previously been suggested that this tendency might be due to subjects
623 confusing the middle location with the gravity location due to their adjacent spatial proximity
624 (Hood, 1999). This seems plausible where there is no clear separation between adjacent search
625 locations, as has been the case in many non-human animal versions of the diagonal tube task,
626 including Osthaus et al. (2003). However, we deliberately modified our apparatus from Osthaus
627 et al.'s (2003) to provide clear separation between the three search locations (and make the setup
628 more similar to previous child studies), yet dogs still showed a tendency to search the middle
629 location. Another possible explanation for searching the middle location is that, if dogs have
630 some notion of the correct search location, and also a (weak?) gravity bias, then their tendency to
631 search the middle location might reflect a kind of naïve averaging of competing biases. We
632 explore this option in Experiment 3, but first, in Experiment 2, we replicate Osthaus et al.'s

633 (2003) Experiment 3 with a larger sample, to re-visit how dogs' search shifts when searching the
634 middle location is not an option. Will they be more successful at locating the reward, or will they
635 be more likely to search the gravity location when the middle option is removed?

636 **Experiment 2: No middle search location**

637 In Experiments 1a-1c, in trials where dogs erred they were significantly more likely to
638 search the middle location than the gravity location. This was also the case for dogs in Osthaus et
639 al. (2003), and a tendency to search the middle location has also been reported for cotton-top
640 tamarins (Hood et al., 1999) and marmosets (Hauser et al., 2001). This raises the possibility that,
641 rather than a gravity bias, dogs (and possibly monkeys) have some sort of bias to search the
642 middle location. Alternatively, perhaps several competing biases influence dogs' search behavior;
643 it is possible that dogs do have a weak gravity bias, but that this is masked by a stronger bias to
644 search the middle location. Therefore, of interest is how dogs re-distribute their search when the
645 middle option is removed; i.e., is the tendency to search the middle masking an ability to solve
646 the task, or potentially masking a gravity bias? Osthaus et al. (2003) tested 8 dogs with a
647 comparable version of the task; in Experiment 2 we replicate this experiment with a larger
648 sample of 16 dogs.

649 **Subjects.**

650 Sixteen dogs (10 male, 6 female; mean age = 45 ± 9 months) participated in Experiment
651 2 (Table S1). Two additional dogs were tested but excluded because they did not complete the
652 test trials (1), or because the session was disrupted by outside noise (1).

653 **Materials.**

654 The apparatus used in Experiment 2 was identical to Experiment 1a, except for that the
655 middle cup was not present during cup pre-training trials or test trials, so there were only two

656 possible search locations, both in the cup pre-training trials and the test trials (gravity and
657 correct; Fig. 4a). The light freeze-dried liver treats were used and the electric fan was switched
658 on to mask any residual sound.

659 **Results.**

660 On average, dogs required 8.1 ± 0.9 trials (mean \pm SEM; range = 6 – 18; median = 6) to
661 reach criterion in the cup pre-training trials. In the first test trial, 6/16 dogs searched the correct
662 location, which did not differ from chance (chance: $16/2 = 8$ dogs searching correctly; binomial
663 test: $p = 0.454$).

664 Across the 12 test trials, 63% of searches were directed to the gravity location (mean_{gravity}
665 = 7.5 ± 0.8 trials), and 37% of searches were directed to the correct location (mean_{correct} = $4.5 \pm$
666 0.8 trials; Fig. 5a). A mixed effects logistic regression model revealed that, while dogs as a group
667 were more likely to search the gravity location than the correct location, this did not quite reach
668 significance ($z = -1.86$, $p = 0.063$; Fig. 5a). Dogs' performance improved significantly across the
669 session (trial log odds = 0.12, $z = 2.39$, $p = 0.017$; Fig. 4a; Fig. 5b; Table S2).

670 We also examined individual performance, and whether individual dogs had a preference
671 for either of the search locations. One dog searched correctly significantly more often than
672 expected by chance across twelve trials (11/12 trials correct, $p = 0.006$); and 6/16 dogs exhibited
673 a significant preference to search the gravity location (10/12 – 12/12 trials; binomial test: $p <$
674 0.039 , see Table S4 for apparatus configuration information for these dogs).

675 **Discussion.**

676 These results suggest that, when there is no middle location to search, dogs' tendency to
677 search the middle location gets shifted to the gravity location. In contrast to our findings in this
678 experiment, dogs tested with a comparable setup in Osthaus' et al's (2003) Experiment 3 seemed

679 to shift to searching the correct location, though only 8 dogs were tested so direct comparison of
680 findings is challenging. Common marmosets on the other hand shifted to searching the gravity
681 location when the middle cup was removed (Cacchione & Burkhardt, 2012). On the basis of our
682 results in the present experiment, should we therefore conclude that dogs have a weak gravity
683 bias that is masked by a stronger preference to search the middle location?

684 Our Experiment 2 results do indeed raise the possibility that gravity might influence
685 dogs' search, at least in certain contexts. However, with the middle location removed, the gravity
686 cup is quite clearly the most proximal of the two cups to the top of the tube—i.e. the location
687 from which the reward is dropped (and therefore last seen by the dog). It is possible that with the
688 middle cup removed, this proximity relationship becomes more salient, and thus becomes the
689 key factor guiding dogs' search. This possibility is particularly important to explore with dogs,
690 given that there is evidence that proximity to reward influences their choices in other physical
691 problem-solving tasks (e.g. string-pulling, Osthaus et al., 2005). Indeed Hood et al. (1999)
692 suggest that tamarins perhaps did not differentiate the gravity and middle locations, because both
693 are closer to the reward's drop-off point than the correct location—thus implying a potential role
694 for proximity. However, the role of proximity in the diagonal tubes task has to our knowledge
695 never been explicitly tested. In Experiment 3 we de-confound gravity and proximity, with the
696 aim of establishing whether our findings in Experiment 2 are due to dogs exhibiting a bias to
697 search on the basis of gravity, or whether in fact proximity might be guiding their search.

698 **Experiment 3: Teasing apart the influence of gravity, proximity and middle biases**

699 To attempt to tease apart whether dogs' search in Experiment 2 was influenced by gravity
700 or proximity, in Experiment 3 we pit gravity *against* proximity, by configuring the apparatus so
701 that the gravity location is a greater distance from the top of the tube (where the reward is last

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702 seen by the dog) than the correct location (see Fig. 4b and 4c). To our knowledge these versions
703 of the diagonal tube task have not previously been presented to any species.

704 In Experiment 3a, an opaque tube was configured either top left-shelf middle, or top
705 right-shelf middle (Fig. 4b). Because in this configuration, the correct, proximal location was
706 also in the center of the apparatus, and we know from Experiment 1 that dogs tend to search the
707 middle (although here the 'middle' location was on top of the shelf rather than the base of the
708 apparatus, and was not in the middle in the sense of being the central of three cups), in
709 Experiment 3b we presented dogs with a version of the task where the spatial relationships
710 between the tube and the search locations were the same as in Experiment 3a, but the entire
711 configuration was shifted, so that the correct search location was no longer in the center of the
712 apparatus.

713 These two experiments together enable us to make a series of predictions regarding how
714 dogs should perform, depending on the relative influence of different factors (gravity, proximity,
715 middle) on their search behavior. First, if dogs' search is primarily influenced by gravity, then
716 they should perform similarly poorly (below chance) in Experiments 3a and 3b, because the
717 gravity location is incorrect in both cases. Second, if search is instead primarily guided by
718 proximity, dogs should be equally successful (above chance) in Experiments 3a and 3b, because
719 the most proximal location is the correct search location in both cases. Finally, if some sort of
720 middle bias has the strongest influence on where dogs search, then performance should be better
721 in Experiment 3a (where the correct location is in the center) than in Experiment 3b (where the
722 incorrect/gravity location is in the center).

723 **Experiment 3a: Gravity vs. Proximity/Middle**724 **Subjects.**

725 Sixteen dogs (6 male, 10 female; mean age = 51 ± 9 months) participated in Experiment
726 3a (Table S1). Four additional dogs were tested but excluded because they did not reach criterion
727 in the cup pre-training trials (1), or because they did not complete the cup pre-training trials (1)
728 or the test trials (2).

729 **Materials.**

730 The configuration of the apparatus used in Experiment 3a is shown in Fig. 4b. There
731 were two possible search locations both in the cup pre-training trials and the test trials: a gravity
732 location that was either on the bottom left or right, and a correct location that was in the center,
733 but on top of the mid-section of the frame, so that it was also the most proximal location to the
734 starting point of the reward. The light freeze-dried liver treats were used and the electric fan was
735 switched on to mask any residual sound.

736 **Results.**

737 On average, dogs required 9.4 ± 0.8 trials (mean \pm SEM; range = 6 – 14; median = 9) to
738 reach criterion in the cup pre-training trials. In the first test trial, 11/16 dogs searched the correct
739 location, which did not differ from chance (chance: 8 dogs searching correctly; exact binomial
740 test: $p = 0.21$).

741 Across the 12 test trials, 73% of searches were directed to the correct location (mean_{correct}
742 = 8.8 ± 0.8 trials; Fig. 5a), and just 27% of searches to the gravity location (mean_{gravity} = 3.3 ± 0.8
743 trials). Dogs as a group searched the correct location significantly more often than expected by
744 chance ($z = 2.867$, $p = 0.004$; Fig. 5a); that is, they were more likely to search the correct,
745 proximal location than the gravity location. The mixed effects logistic regression model revealed

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746 no change in performance across trials (trial log odds = 0.06, $z = 1.00$, $p = 0.316$; Fig. 4b; Fig.
747 5b; Table S2).

748 We also examined individual performance, and whether individual dogs had a preference
749 for either of the search locations. Half of the dogs (8/16) searched the correct/middle location
750 significantly more often than expected by chance across twelve trials (10/12 – 12/12 trials
751 correct; binomial test: $p < 0.039$, see Table S4 for apparatus configuration information for these
752 dogs). Only one dog exhibited a significant preference to search the gravity location (12/12 trials,
753 $p < 0.001$, Table S3).

754 **Discussion.**

755 Based on the results of Experiment 3a, we can already eliminate the first option outlined
756 above—that in Experiment 2, when the middle cup was removed, dogs' search was primarily
757 influenced by gravity. If that were the case then dogs should have performed badly in this
758 version of the task (i.e., they should have searched the gravity location), when in fact their
759 performance was above chance. However, the results of this experiment alone cannot tell us
760 whether dogs are searching on the basis of proximity—it is also possible that dogs in this
761 experiment were searching the 'middle' location, in the sense that the correct cup was in the
762 absolute center of the apparatus (on a horizontal plane). In Experiment 3b we aimed to establish
763 whether dogs' search is more strongly influenced by proximity to the reward's starting point, or a
764 preference for searching at the center of the apparatus.

765 **Experiment 3b: Gravity/Middle vs. Proximity**766 **Subjects.**

767 Sixteen dogs (7 male, 9 female; mean age = 57 ± 11 months) participated in Experiment
768 3b (Table S1). Four additional dogs were tested but excluded because they didn't reach criterion
769 in the cup pre-training trials (2), or because they did not complete the test trials (2).

770 **Materials.**

771 The configuration of the apparatus used in Experiment 3b is shown in Fig. 4c. The
772 configuration was the same as for Experiment 3a in terms of the spatial relationships between the
773 search locations and the reward's starting point (i.e. there was a gravity location and a more
774 proximal correct location), but the entire configuration was shifted within the frame of the
775 apparatus, so that the gravity location was bottom middle, and the correct location on top of the
776 mid-section of the frame was either on the left or the right. The light freeze-dried liver treats
777 were used and the electric fan was switched on to mask any residual sound.

778 **Results.**

779 On average, dogs required 10.75 ± 1.24 trials (mean \pm SEM; range = 6 – 21; median = 9)
780 to reach criterion in the cup pre-training trials. In the first test trial, 4/16 dogs searched the
781 correct location, which did not differ significantly from chance (chance: 8 dogs searching
782 correctly; binomial test: $p = 0.077$).

783 Across the 12 test trials, 35% of searches were directed to the correct location (mean_{correct}
784 = 4.2 ± 1.0 trials; Fig. 5b), and 65% of searches to the gravity location (mean_{gravity} = 7.8 ± 1.0
785 trials). Thus, while dogs tended to search incorrectly, overall performance did not quite reach
786 significance ($z = -1.895$, $p = 0.058$; Fig. 5b). As in Experiment 3a, the mixed effects logistic

787 regression model revealed no change in performance across trials (trial log odds = 0.08, $z = 1.50$,
788 $p = 0.132$; Fig. 4c; Fig. 5b; Table S2).

789 We also examined individual performance, and whether individual dogs had a preference
790 for either of the search locations. One dog searched correctly significantly more often than
791 expected by chance across twelve trials (12/12 trials, $p < 0.001$); and 8/16 dogs exhibited a
792 significant preference to search the gravity/middle location (10/12 – 12/12 trials; binomial test: p
793 < 0.039 , Table S3, see Table S4 for apparatus configuration information for these dogs).

794 **Discussion.**

795 This shift from above-chance performance in Experiment 3a to close-to-below-chance
796 performance in Experiment 3b, despite the fact that the spatial relationship between the tube and
797 the two search locations was the same in both cases, demonstrates that above all else, dogs'
798 search is directed to the center of the apparatus. This result is in line with Osthaus et al.'s (2003)
799 Experiment 4, which showed that dogs searched the 'gravity location' more often when it was
800 located bottom-middle, and also searched correctly more often when the correct location was
801 bottom-middle. This finding also enables us to rule out several previously posited explanations
802 for why individuals tend to search the middle location in 3-cup versions of the diagonal tube
803 task. First, it eliminates the possibility that dogs search the middle location because they confuse
804 it spatially with the gravity location, as suggested by Hood et al., (1999), as in our Experiments
805 3a and 3b the middle and gravity locations are clearly physically separated, both horizontally and
806 vertically. Therefore, it seems infeasible that dogs could confuse the two locations spatially.
807 Second, it also rules out the possibility that dogs are performing some sort of naïve averaging
808 that leads them to search in the center, because here there are only two available search options.
809 Finally, it also excludes the suggestion that individuals search the middle because the middle and

810 gravity locations are both closer to reward's dropping point than the correct location (Hood et al.,
811 1999), as this was not true in our Experiment 3b, where the correct location was in closer
812 proximity to the reward's dropping point than the middle location.

813 **Experiment 4: Does removing sources of bias reveal successful performance?**

814 While we have found no evidence of dogs exhibiting gravity-biased search, it appears
815 likely that their performance in the diagonal tube task is limited by a preference to commence
816 searching at the center of the apparatus. It is possible that contextually inappropriate responses
817 elicited by the setup of the task (e.g., an inability to inhibit searching particular preferred
818 locations) is masking dogs' physical-causal knowledge and ability to succeed at the task (e.g.,
819 Gómez, 2005). Therefore, in our final experiment, we investigated how dogs would perform in a
820 version of the diagonal tube task described in Gomez (2005), in which all potential sources of
821 bias examined in the previous experiments are eliminated.

822 Specifically, in Experiment 4 there was no gravity location, no middle location, and no
823 most proximal location because the two search locations were equidistant from the reward's
824 starting point; i.e., there was no plausible physical reason to choose the distractor cup (Fig. 4d).
825 According to Southgate and Gomez's unpublished data described in Gomez (2005), when
826 presented with this version of the diagonal tube task, macaques were still unable to successfully
827 locate the reward. We were interested in whether eliminating these potential sources of search-
828 bias might either reveal understanding of the physical-causal structure of the task in dogs, or at
829 least enable them to better attend to relevant cues (i.e. the location of the cup connected to the
830 bottom of the tube).

831 **Subjects.**

832 16 dogs (10 male, 6 female; mean age = 41 ± 7 months) participated in Experiment 4
833 (Table S1). No dogs had to be excluded from this experiment.

834 **Materials.**

835 The tube was opaque and positioned either top middle-bottom right, or top middle-
836 bottom left. As in Experiment 2, the middle cup was not present so there were only two possible
837 search locations, both in the cup pre-training trials and the test trials (correct and incorrect). This
838 meant that as well as being no middle location, there was also no gravity location. The light
839 freeze-dried liver treats were used and the electric fan was switched on to mask any residual
840 sound.

841 **Results.**

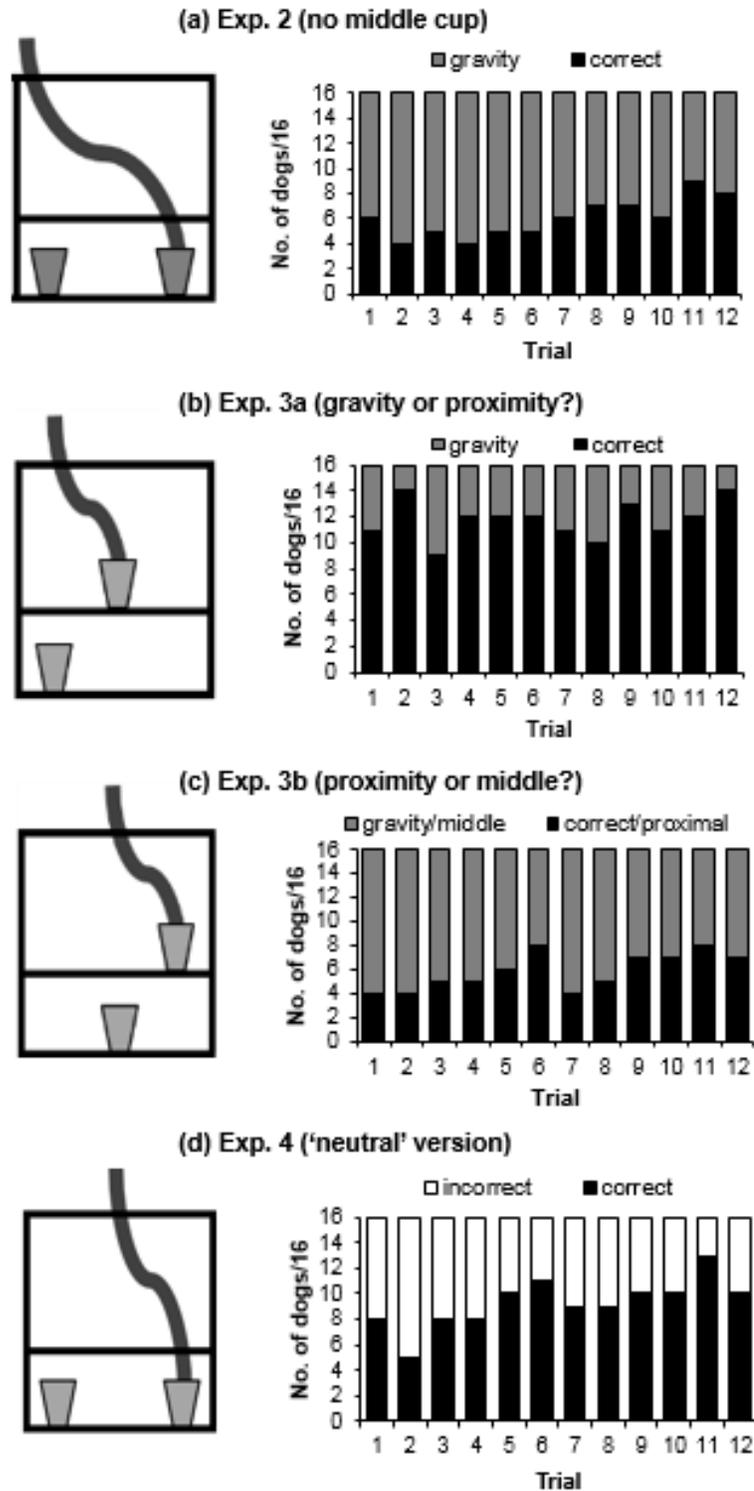
842 On average, dogs required 7.1 ± 0.4 trials (mean \pm SEM; range = 6 – 10; median = 6) to
843 reach criterion in the cup pre-training trials. Dogs did not show a bias for searching any
844 particular location in their first trial; 8/16 dogs searched the correct location and 8/16 dogs
845 searched the incorrect location (chance: 8 dogs searching correctly; binomial test: $p = 1.00$).

846 Across the 12 test trials, 58% of searches were directed to the correct location (mean_{correct}
847 = 6.9 ± 1.0 trials; Fig. 5a), and 42% of searches to the incorrect location (mean_{incorrect} = 5.1 ± 1.0
848 trials). Dogs as a group failed to search the correct location significantly more often than
849 expected by chance (mean_{correct} = $z = 1.08$, $p = 0.28$; Fig. 5a), though according to the mixed
850 effects logistic regression model, their performance improved significantly across the session
851 (trial log odds = 0.17, $z = 3.00$, $p = 0.003$; Fig. 4d; Fig. 5b; Table S2).

852 We also examined individual performance, and whether individual dogs had a preference
853 for either of the search locations. Six dogs searched correctly significantly more often than

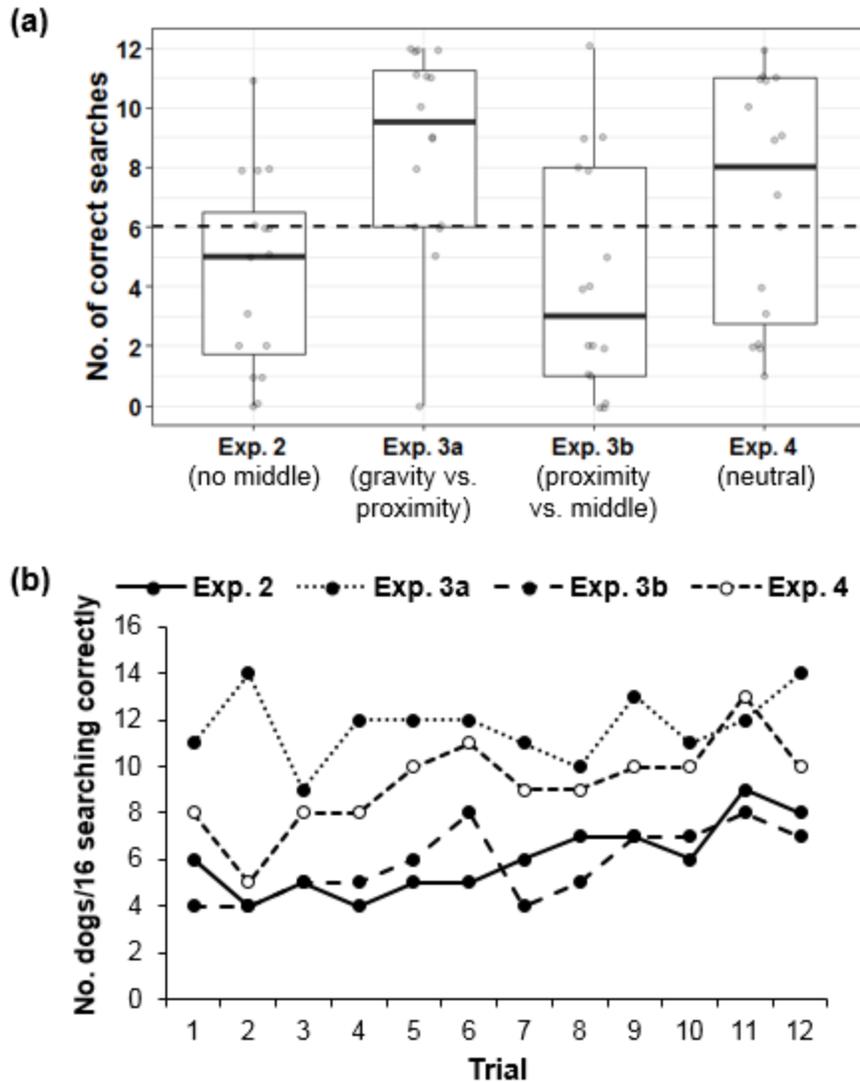
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854 expected by chance across twelve trials (10/12 – 12/12 trials, binomial test: $p < 0.039$). Four
855 dogs exhibited a significant preference for the incorrect location (10/12-11/12 trials, $p < 0.039$,
856 Table S3, see Table S4 for apparatus configuration information for these dogs).
857



858

859 **Figure 4.** Schematic representation of the configuration of the apparatus and the number of dogs searching
 860 each location across trials 1-12 in Experiments 2-4 where there were always two search locations. Black
 861 indicates correct cup; light-grey indicates middle cup; white indicates incorrect cup, which in Exp. 4 was
 862 neither in the gravity nor middle location
 863



864

865 **Figure 5.** (a) Box plot showing the number of searches directed at the correct location in Experiments 2
 866 (no middle location), 3a (gravity vs. proximity), 3b (gravity vs. middle) and 4 ('neutral' version). The
 867 dashed horizontal line represents the expected number of searches per location if search was random. (b)
 868 Comparison of the number of dogs out of 16 that searched the correct location in each trial in Experiments
 869 2, 3a, 3b and 4
 870

871 **Discussion.**

872 By removing the gravity and central locations, and making both search options equally
 873 proximal to the reward's dropping point we eliminated potential cues that could be influencing
 874 dogs' search behavior. If search biases were masking dogs' actual knowledge of the physical-
 875 causal structure of the task in previous experiments, then we would have expected them to

876 succeed here. This was not the case—although the majority of searches were directed to the
877 correct location, overall performance was not better than chance. However, performance was
878 improved relative to some of our other experiments (Fig. 5, see next section for model
879 comparing these experiments), providing some evidence that eliminating sources of bias may
880 have helped dogs to some extent; potentially by enabling them to focus on the relevant cue of the
881 tube.

882 **Comparison of performance in Experiments 2 – 4 and interim discussion**

883 In Experiments 2–4, dogs were presented with versions of the diagonal tube task where a
884 treat was dropped down a diagonal tube, and there were two possible search locations.
885 Experiment 2 was a replication of Osthaus et al.'s (2003) Experiment 3 but with a larger sample
886 of dogs, and Experiments 3a, 3b and 4 were novel variations of the diagonal tube task for dogs,
887 designed to further probe what factors guide dogs' search, and explore how dogs perform when
888 these potential sources of bias are eliminated from the testing setup.

889 We used mixed effects logistic regression that assumed a fixed slope across subjects to
890 compare dogs' ability to search correctly between Experiments 2, 3a, 3b and 4 (Table S6). Dogs
891 were significantly more likely to search the correct location when it was positioned in the middle
892 of the apparatus and most proximal to the point where it was last seen (Exp. 3a), compared with
893 in Experiment 2 where there was no middle cup (log odds = 2.23, $z = 3.49$, $p < 0.001$) and
894 compared with Experiment 3b, when the incorrect/gravity location was in the middle (log odds =
895 2.42, $z = 3.58$, $p < 0.001$; Fig. 5a and 5b). Dogs also performed better in Experiment 4 where
896 potential sources of bias were eliminated than in Experiment 3b (log odds = 1.46, $z = 2.21$, $p =$
897 0.027). There were no other significant differences between experiments in terms of dogs' ability

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898 to search correctly, though there was a pattern of greater success in Experiment 4 compared to
899 Experiment 2 (log odds = 1.27, $z = 1.94$, $p = 0.052$; Fig. 5b and 5c).

900 When the middle search location was removed (Experiment 2), rather than improving
901 performance, dogs' search shifted to the gravity location, which suggested that in addition to
902 having a preference to search the middle, search behavior might also be influenced (to a lesser
903 extent) by gravity, or potentially proximity. In Experiment 3a, dogs were able to locate the
904 reward significantly more often than expected by chance, which when considered in isolation,
905 lent support to the idea that proximity, not gravity might be guiding dogs' search. However, when
906 the same configuration was shifted within the frame of the apparatus so that the correct (still
907 most proximal) location was on the left or right and the gravity location was now in the center of
908 the apparatus (Experiment 3b), dogs no longer succeeded at locating the reward: again, they
909 directed their search to the central location. Dogs' performance did not change across trials in
910 either of these experiments—in Experiment 3a they performed consistently well and in
911 Experiment 3b they performed consistently badly—reflecting their tendency to perseveratively
912 search the middle location in both experiments. This finding for Experiment 3b in particular
913 suggests that their preference to search in the center is difficult to overcome—even despite never
914 being reinforced for searching centrally in Experiment 3b they continued to do so across repeated
915 trials. Taken together, this suggests that when additional information regarding the reward's
916 movement/the tube's mechanism is lacking, dogs default to searching in the center of the
917 apparatus.

918 In Experiment 4, dogs' performance was significantly improved relative to Experiment
919 3b but not better than chance. This suggests that eliminating potential sources of bias may go
920 some way to improving dogs' search for a reward invisibly displaced down a diagonal tube, but

921 does not reveal successful performance, i.e., it is not the case that search biases are masking
922 dogs' true knowledge of the physical-causal structure of the task (Gomez, 2005).

923 **General Discussion**

924 The tubes task has been used widely in the fields of cognitive development and
925 comparative cognition to investigate children's and animals' physical reasoning abilities,
926 specifically regarding their expectations about the influence of gravity on unsupported objects.
927 By carefully manipulating the availability of perceptual cues (Experiments 1a-c) and the relative
928 positions of various components of the apparatus (Experiments 2–4) we have revisited previous
929 versions of the diagonal tube task and presented dogs with several novel versions of the task in
930 an attempt to elucidate what factors really guide their search for a reward dropped down a
931 diagonal tube.

932 Dogs as a group were generally unable to solve the diagonal tube task across 12 trials,
933 though in most experiments their performance gradually improved over the course of the session
934 suggesting that they would learn to succeed eventually, though likely via reinforcement rather
935 than understanding anything about the physical-causal structure of the task. This is in keeping
936 with the findings of Osthaus et al. (2003), who likewise reported that dogs were initially
937 unsuccessful in the diagonal tube task, but learned to locate the reward across a limited number
938 of trials. The results of Experiment 4—where we eliminated the potential for dogs to search on
939 the basis of a gravity, middle or proximity bias—provide support for dogs' lack of causal
940 understanding, because if it were the case that successful performance was being masked in other
941 versions by an inability to suppress some search bias(es), dogs should have succeeded here.

942 A lack of ability to reason about the constraints imposed by the tube to locate hidden food
943 fits with dogs' performance in other physical-causal reasoning tasks, where they have been

944 outperformed by great apes (Bräuer et al., 2006) and wolves (Lampe, Bräuer, Kaminski, &
945 Virányi, 2017). Solving the diagonal tube task by reasoning about its physical-causal structure
946 requires knowledge of object permanence, invisible displacement, object solidity and gravity, as
947 well as the ability to elicit an appropriate search response (Tecwyn & Buchsbaum, in press).
948 Although there is some evidence that dogs may possess an implicit understanding of object
949 solidity based on looking-time experiments (Pattison, Miller, Rayburn-Reeves, & Zentall, 2010),
950 studies that have investigated whether they can accurately search for invisibly displaced objects
951 have proven inconclusive (e.g., Collier-Baker, Davis, & Suddendorf, 2004; Fiset & Leblanc,
952 2007; Miller, Rayburn-Reeves, & Zentall, 2009), with dogs only compellingly passing specific
953 simplified versions of invisible displacement tasks (e.g., Miller et al., 2009; Zentall & Pattison,
954 2016).

955 While dogs generally failed to search correctly in the diagonal tubes task, their errors
956 were not of the same nature as those observed in children. Specifically, we found no evidence
957 that dogs exhibit a gravity bias in the diagonal tube task, either across trials or in trial 1. In fact,
958 in all of the 3-cup versions of the task (Experiments 1a–c), when dogs searched incorrectly they
959 were significantly more likely to search the middle location than the gravity location. Even in
960 experiments where dogs did mainly search the gravity location (Exp. 2 where there was no
961 middle cup, and Exp. 3b where the gravity cup was in the middle), the distribution of their
962 searches did not differ from chance. It is possible that the incorporation of a tube familiarization
963 phase in the present study could have diminished dogs' gravity bias relative to that reported by
964 Osthaus and colleagues (e.g., our Experiment 1a: 6/16 trial 1 gravity searches; Osthaus et al.'s
965 (2003) comparable Experiment 1 diagonal condition: 8/16 gravity searches). However, given that

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966 overall our results generally replicated those of Osthaus et al., the tube familiarization appears
967 not to have had a great impact on performance.

968 Why would dogs not exhibit a gravity bias? After all, they are subject to the same laws of
969 physics as young children, and both species exist in a world where objects do typically fall
970 straight down. Further, it seems likely that dogs have much experience of seeing objects (e.g.,
971 food, balls) being dropped onto the ground. One possibility is that even if dogs are able to predict
972 that a dropped object will fall straight down, their cognition is fundamentally different to that of
973 humans and they do not form a naïve theory on the basis of this information. This could also
974 explain the qualitative difference in the gravity bias seen in children versus some other
975 primates—perhaps only humans form and reason on the basis of a naïve theory of gravity, which
976 results in perseverative searching of the gravity location. Other species (e.g., cotton-top tamarins)
977 might predict that an unsupported item will fall straight down, but because they have not formed
978 a robust theory about this, searching of the gravity location rapidly decreases after trial 1.
979 Relatedly, this prediction may not transfer to a situation where the object immediately moves out
980 of sight (as is the case when it is dropped into an opaque tube). An alternative possibility is that
981 human infants learn about the properties and behavior of objects, including the effect of gravity
982 on objects, through their own actions—we are all familiar with toddlers in high chairs repeatedly
983 throwing things onto the floor. Dogs' anatomy does not afford the same opportunity to act on
984 objects and therefore limits the extent to which they are able to learn from observing the effects
985 of their own actions on these objects. Presenting human infants who have not yet started
986 manually interacting with objects with a either an eye-tracking or looking time version of the
987 diagonal tube task could enable investigation of this; if repetitive experience of acting on objects
988 is critical for the development of a gravity bias, then these infants should not expect the object to

989 end up in the gravity location. Work by Spelke and colleagues (1992) suggests showing 4-month-
990 olds that an item dropped behind an occluder has remained suspended in midair does not appear
991 to violate their expectations, thus lending support to the idea that young infants might not have
992 an expectation that dropped objects will fall straight down to the ground.

993 Adapting looking-based measures with dogs would also enable the investigation of one
994 further possibility: that dogs in fact *do* have a gravity bias (or, indeed, they are able to correctly
995 predict where the reward will end up, as has been found for marmosets; Cacchione & Burkhardt,
996 2012) but this is not revealed by their search behavior. Dissociations between looking-based and
997 action-based measures have been found for the tubes task and other physical reasoning tasks in
998 non-human primates (e.g., Cacchione & Burkhardt, 2012; Santos & Hauser, 2002) as well as
999 young children (e.g., Lee & Kuhlmeier, 2013). Action-based versions of the tubes task pose
1000 executive demands, as well as requiring individuals to use “feedforward logic-causal inferences”
1001 (Cacchione & Rakoczy, 2017), so it is feasible that dogs might predictively look to the gravity
1002 location (or the correct location), but then proceed to search elsewhere.

1003 In all of the experiments where a cup was positioned in the center of the apparatus (Exp.
1004 1a–c; Exp. 3a–b), the majority of dogs' searches were directed to that location. Why might dogs
1005 have a preference to search initially in the middle? A tendency to search the middle has been
1006 observed previously in dogs (Osthaus et al., 2003), as well as in two different monkey species
1007 (Cacchione & Burkhardt, 2012; Hauser et al., 2001; Hood et al., 1999). However, while the
1008 authors of these studies speculated about potential reasons for a tendency to search the middle
1009 location (e.g., spatial confusion between the gravity and middle locations (Hood et al., 1999);
1010 approximation of the reward's position, (Hauser et al., 2001); search the middle when uncertain
1011 (Osthaus et al., 2003)), previous work did not explore these possibilities experimentally. We took

1012 this on in our Experiment 3, the results of which suggested that dogs have a preference to
1013 commence their search at the center of the apparatus, as opposed to spatially confusing the
1014 gravity and middle locations, or engaging in naïve averaging of competing search preferences.
1015 The explanation offered by Osthaus et al. (2003) remains plausible—that when dogs are
1016 uncertain of the reward's location, they commence searching at the center of the apparatus.
1017 Future work could explore whether this strategy is specific to the diagonal tube task (e.g. related
1018 to the constraints of the frame) or a more general strategy under conditions of uncertainty, by, for
1019 example, hiding a reward in one of an array of cups and recording dogs' search behavior. If
1020 searching in the middle reflects a general strategy, dogs should also commence searching
1021 centrally in this context. Experiment 3 also allowed us to rule out the possibility that dogs' search
1022 might be influenced by proximity to the last place the reward was seen, which has never
1023 previously been explored in any species in the vertical version of the tubes task.

1024 The diagonal tube task has been used to study the gravity bias and physical reasoning
1025 abilities in human children and a range of animal species, and so we chose to use this task here in
1026 order to replicate and extend this previous work. However, given that the tube is a very specific
1027 causal mechanism that is likely unfamiliar to dogs (and to animals more generally), future work
1028 should explore dogs' physical reasoning abilities using more ecologically plausible paradigms.
1029 While what is known about domestic dog physical cognition suggests that the species might have
1030 relatively poor skills in this domain, physical and causal reasoning abilities have not been studied
1031 in dogs to the same extent as in other taxa (e.g. primates, corvids, parrots), and some of the more
1032 basic tasks that have been used to investigate intuitions about fundamental object properties such
1033 as solidity and support in other species have been bypassed in favor of more complex designs
1034 (e.g., Müller, Riemer, Range, & Huber, 2014). For example, a search-based version of the table

1035 or shelf task (Cacchione, Call, & Zingg, 2009; Hood et al., 2000; Spelke et al., 1992), suitably
1036 adapted for dogs, could be an appropriate means to investigate dogs' knowledge of solidity, as
1037 well as providing an additional paradigm with which to examine whether dogs' search might be
1038 guided by gravity, as seems to be the case for macaques presented with this task (Hauser et al.,
1039 2001).

1040 Finally, the fact that dogs' performance varied so much in our different versions of the
1041 diagonal tube task setup should serve as an example of the value and importance of running
1042 multiple experiments that carefully manipulate different factors that might influence behavior. If
1043 we had only run Experiment 3a, we could have mistakenly concluded that dogs had a grasp of
1044 the physical-causal structure of the task. If, on the other hand, we had only run Experiment 3b,
1045 we could have—again mistakenly—concluded that dogs had a gravity bias. It is only when we
1046 consider dogs' behavior across multiple experiments that a picture of what might really be
1047 influencing their performance begins to emerge. As ever in animal cognition research, it is
1048 critical to consider what other factors (in addition to the ones being investigated) might be
1049 influencing behavior.

1050 In conclusion, across seven experiments we found no evidence that dogs spontaneously
1051 grasp that the tube constrains the path of the reward and guides it to the cup attached to its
1052 bottom end. However, our data also suggest that this failure is not primarily explained by a
1053 gravity bias. Based on current evidence, it is possible that a gravity bias might be unique to some
1054 primate species, or potentially (given the mixed evidence from non-human primate studies)
1055 unique to young human children. To better understand the origins of the gravity bias and the
1056 mechanisms underpinning it, additional groups should be tested with the diagonal tube task,
1057 ideally using a developmental comparative approach in which evidence for a gravity bias is

1058 examined in immature and mature individuals, across species that differ with respect to their
1059 causal knowledge and inhibitory control skills.

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