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Hood’s Gravity Rules

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Synonyms

Gravity bias; Gravity error; Naïve physics; Tubes task

Definition

The gravity bias or gravity error is the naïve expectation that an unsupported object will fall straight down, regardless of any obstacles that impede, constrain or divert its trajectory. This bias is typically revealed by participants making ‘straight down’ search errors in action-based tasks; most strikingly in the tubes task (Hood, 1995). Specifically, when an object is dropped down an opaque diagonal tube, an individual exhibiting a gravity bias makes a predictable error: they search the location directly beneath the top of the tube that the object is dropped into (‘A’ in Fig. 1a and b), rather than searching the correct location that is connected to the bottom of the tube (‘C’ in Fig. 1a and b). According to Hood’s (1995; 1998) account, an important feature of a naïve gravity bias is that the error is challenging to overcome and persists in spite of counter-evidence. In the tubes task this is exemplified by repeated searching of the gravity location across trials, despite seeing the actual end location of the object each time.

Hood’s discovery of the gravity bias in young children

The gravity bias was first discovered by Bruce Hood (Hood, 1995), who set out to investigate the development of spatial reasoning abilities in young human children (2- to 4.5-year-olds) using the tubes task. In the original version of the task, children were presented with a frame containing between one and three opaque, intertwined tubes, each connected to a cup at the base of the apparatus (Fig. 1). The apparatus was designed so that the top of each tube had a cup directly beneath it (aligned), but the bottom of that tube was always connected to an alternative cup (non-aligned). Children watched an experimenter drop a ball down one of the tubes, and were then encouraged to search for the ball. The experimenter then switched the position of the tube(s), dropped the ball down one of them again, and the child searched again (Hood, 1995, Exp. 1). This was repeated across multiple trials for one- two- and three-tube versions of the task. To an adult, it seems obvious that the ball will end up in the cup connected to the end of the tube that it was dropped down—you simply have to follow the path of that tube from top to bottom. However, while 4-year-olds generally succeeded at all versions of the task regardless of the number of tubes, children up to around 3.5 years of age struggled to locate the ball when multiple tubes were intertwined, and most 2-year-olds could not even pass the simplest one-tube version (Fig. 1b; Hood, 1995).

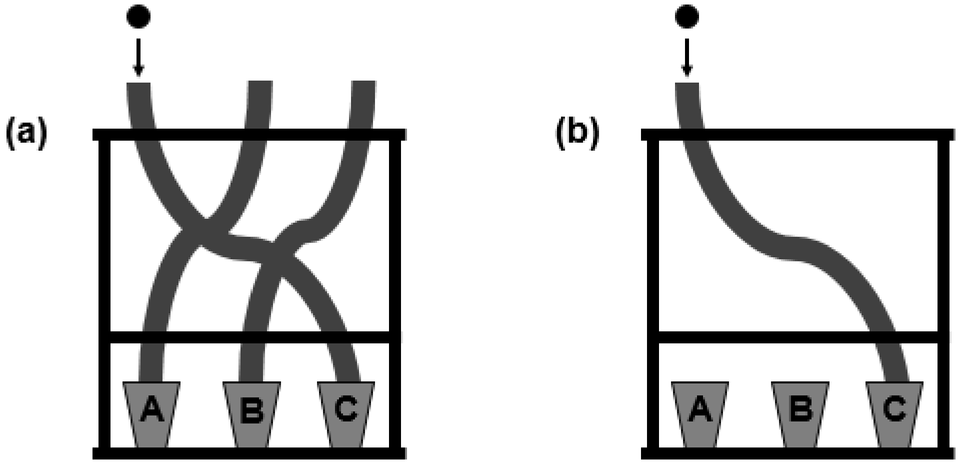

Figure 1. Versions of the tubes task typically used with (a) human children (3 intertwined tubes) and (b) non-human animals (single diagonal tube). A = gravity location, B = middle location, C = correct location.

In examining children's search errors, Hood observed something intriguing: when children searched incorrectly, regardless of their age and the number of tubes, their errors were not randomly distributed; rather, they tended to search the cup aligned directly beneath the top of the tube that the ball was dropped into, or the 'gravity location' ('A' in Fig.1a and b). We will refer to searching the gravity location as the 'gravity error'. Furthermore, even though children were allowed to continue searching until they found the ball on each trial, which meant they received visual feedback regarding the actual end location of the ball, children did not make this mistake only once and then succeed on their next trial; this erroneous searching of the gravity location persisted across multiple presentations of the task.

To see whether it might be the case that switching the configuration of the tube(s) between trials was confusing for the youngest children, causing them to default to searching the gravity location, Hood presented ten 2-year-olds with a simplified version that we will call the 'diagonal tube task' (Hood, 1995, Exp. 4; Fig. 1b). This version involved a single diagonal opaque tube that was configured top-left to bottom-right of the frame, and remained in a fixed position across trials. However, even in this relatively straightforward version of the task, the majority of 2-year-olds persisted in searching the gravity location (bottom left) across trials (trial 1: 9/10, trial 2: 8/10, trial 3: 9/10; overall gravity searches: 62%; Table 1).

This demonstrates that, even when the task is visually less confusing and children are given the opportunity to learn where the item ends up (because it ends up in the same place on every trial), 2-year-olds show a persistent gravity bias according to their search behavior (Hood, 1995). Nine out of the ten children tested eventually learned to solve this task (based on a criterion of five consecutive correct searches), after which the configuration of the tube was switched so it was positioned top-middle to bottom-left of the frame, and a single trial presented. Five of the nine children reverted to a gravity bias and searched the new gravity location (the bottom middle location), suggesting that they had previously learned to succeed based on reinforcement (i.e., learning the correct location to search across trials), rather than coming to understand the tube's physical-causal mechanism. The gravity bias is described as 'theory-like' on the basis that, like formal theories, it produces behavior that is initially challenging to overcome (Hood, Wilson, & Dyson, 2006), even in the face of contradictory evidence, as exemplified by perseverative search of the gravity location despite receiving visual feedback regarding the correct end location of the ball.

Subsequent developmental studies

Since Hood’s (1995) seminal study, the gravity bias seen in young children has been shown to be a robust effect that has been replicated across several different studies and research groups (e.g. Bascandziev & Harris, 2010; Baker, Gjersoe, Sibielska-Woch, Leslie, & Hood, 2011; Freeman, Hood, & Meehan, 2004; Hood, Wilson, & Dyson, 2006; Jaswal, 2010; Joh & Spivey, 2010). In the following section, we discuss studies that have attempted to uncover the mechanisms underpinning young children’s gravity bias, as well as how children are ultimately able to overcome searching on the basis of this bias. These studies suggest that (1) understanding the causal mechanism of the tube, and (2) inhibitory control both have a role to play.

Understanding the causal mechanism of the tube

Although at first glance solving the tubes task appears fairly simple, knowing how the hollow tube affects where the dropped object will end up requires several pieces of knowledge about the physical world. Necessary prerequisites for searching correctly in the tubes task include knowledge of object permanence, invisible displacement, object solidity, containment, gravity, and how these factors interact to constrain the path of the object through the tube. It is therefore possible that young children fail to locate the reward because they do not understand the tube’s causal mechanism; i.e., that it is hollow and constrains the reward’s path as it travels through it.

Indeed, there is evidence that acquiring knowledge about the physical-causal mechanism of the tube is important for success in the tubes task, and results from other tasks suggest that physical reasoning skills do improve between 2- and 3.5-years (Seed & Call, 2014). Several studies have shown that manipulations to the tubes task that highlight the causal role of the tube in some way can improve performance and reduce searching of the gravity location. Modifications that have enabled children to perform better include: making the openings at the top of the tubes more visible (Bascandziev & Harris, 2011); verbal testimony about the causal role of the tube in constraining the object's movement (Bascandziev & Harris, 2010); instructing children to imagine the ball rolling down the tube (Joh, Jaswal, & Keen, 2011; Palmquist, Keen, & Jaswal, 2018); and making the tubes different colors to accentuate their separate trajectories (Joh & Spivey, 2012). Thus, better understanding of the tube's causal mechanism likely contributes to children's ability to overcome their gravity bias by around 4 years of age. However, as another series of studies suggests, poor understanding of the tubes' causal mechanism does not fully explain younger children's gravity-biased search.

Gravity-specific Bias

If a general inability to understand the causal mechanism of the tube was the sole factor leading children to make a gravity error, then they would be expected to make a comparable error in other tasks involving the invisible displacement of objects through tubes. For instance, it is possible that searching the 'gravity location' could reflect a more general incorrect causal belief that moving objects travel in a straight line, or a default strategy of searching the location closest to where the object was dropped from.

However, this does not appear to be the case. In one study, when children were shown video footage of the tubes task that involved upwards motion (where the ball was 'sucked up' a tube), they were more likely to correctly identify the end location of the ball compared with when the task involved downwards (i.e., gravity-based) motion (Hood, 1998). A horizontal version of the tubes task revealed a similar pattern of results (Hood, Santos, & Fieselman, 2000)—2-year-olds who were presented with both vertical and horizontal trials with the tubes apparatus were more successful at locating a ball when it moved horizontally through a tube compared with when it fell vertically. Children's better performance in versions of the task involving upward and horizontal motion demonstrates that children who exhibit a gravity error in the original version of the tubes task are better able to understand the tube's physical mechanism under other conditions. These findings provide evidence that the nature of young children's search error in the tubes task is specific to falling/gravity-based displacement events, as opposed to being explained by a more general straight-trajectory bias or a proximity bias.

Taken together, these studies suggest that the gravity error in children reflects a naïve theory that all dropped objects fall straight down, even if their path is constrained or redirected. Why might a gravity specific bias exist? It seems likely that the gravity error is based on experience of the ubiquitous influence of gravity on objects in the world; specifically, experience of observing falling objects and seeing where they land (Hood et al., 1999; 2000). Indeed, in most cases objects *do* in fact land straight below the location they fell from, so this is usually a sensible heuristic to follow. Data from humans infants seem to support this idea: four-month-old humans are not sensitive to the influence of gravity on falling objects according to a looking-time measure (Spelke et al., 1992), and even at 10-months infants do not seem to expect an object travelling in a straight line to continue to do so (Spelke, Katz, Purcell, Ehrlich, & Breinlinger, 1994). However, with the development of motor skills experience of dropping objects increases in frequency which could lead to the development of a gravity bias.

Inhibitory control

Inhibitory control – specifically, the ability to inhibit responding on the basis of a naïve theory of gravity – is also thought to play a central role in the ability to correctly search for the object in the tubes task. Children's performance in the horizontal and upwards tubes tasks suggest that their naïve gravity bias may be competing with their emerging understanding of the tubes' causal mechanism, leading to poorer performance when the two are in conflict, and the gravity bias must be inhibited. Evidence for the role of inhibitory control in successful performance in the tubes task comes from a study showing that four-year-old children who pass the standard 3-tube version of the task revert to searching the gravity location if two balls are dropped simultaneously, thus increasing the task's attentional demands and cognitive load (Hood et al., 2006). Additionally, 3-year-olds' ability to search correctly in the standard version of the task was significantly correlated with their performance in an unrelated task where it was necessary to inhibit a prepotent response (Baker, Gjersoe, Sibielska-Woch, Leslie, & Hood, 2011), suggesting that an ability to inhibit an underlying gravity bias might be playing a role in their performance.

Thus, it seems that in the case of the original version of the tubes task, children’s tendency to search the vertically aligned container is best explained by a bias that is specific to gravity-based invisible displacement. At two years of age, children may lack complete understanding of the tube mechanism, and also have relatively weak inhibitory control skills, and so are unable to inhibit searching on the basis of their gravity bias. Older children (i.e., four-year-olds) who have developed sufficient inhibitory skills and an understanding of the tube’s causal mechanism typically search correctly, but revert to gravity-based search when their cognitive skills are taxed, thus suggesting that the bias continues to exist, but is usually ‘dormant’.

Explicit vs. implicit measures of the gravity bias

All of the tubes task studies discussed so far have used search behavior as a measure of understanding; i.e. they have all used action-based (‘explicit’) measures. However, in addition to possessing the prerequisite knowledge about the physical world to be able to infer where the object will end up, and being able to inhibit responding on the basis of a gravity bias, asking participants to search for the object also necessitates holding a representation of the object in mind, and generating an appropriate search response. It is possible that the additional demands posed by requiring participants to search for the item tax young children’s limited cognitive resources and thus contribute to gravity-biased search. To investigate whether this is the case, different measures based on e.g., looking-time or gaze direction (‘implicit’ measures), which eliminate the additional task demands, can be used.

Only one study (Lee & Kuhlmeier, 2013) has explored how children perform in the tubes task according to an implicit measure. Two-year-olds were presented with one-tube and two-tube versions of the task. However, rather than allowing participants to search for the ball, Lee & Kuhlmeier (2013) measured their eye gaze patterns (implicit measure) and pointing behavior (explicit measure). In the one-tube version, all children directed their gaze to the correct location, but only some also pointed to this location. In the two-tube version, neither looking nor pointing was directed to the correct location. When children made pointing errors, they tended to be directed at the gravity location, corroborating the findings of previous studies where children had to actively search for the object (Hood, 1995). However, some children who incorrectly pointed at the gravity location in the one-tube version directed their gaze to the correct location at the end of the tube (when there were two tubes, which increased the complexity of the task, two-year-olds both looked and pointed at the gravity location). Thus, according to their spontaneous eye movements, some two-year-olds were implicitly aware of the end location of the ball in the one-tube version of the task, even though they were not able to elicit a correspondingly correct pointing response. This provides evidence for a potential dissociation between implicit and explicit measures in the diagonal tube task: some children’s eye-gaze was directed towards the correct location, whereas their pointing behavior appeared to be guided by a gravity bias (Lee & Kuhlmeier, 2013). Based on current evidence it is not clear what might explain this dissociation between the two behavioral measures; differences in processing load (with pointing demanding more processing resources than spontaneous looking), or the nature of the underlying representation required to support the different behaviors (a stronger representation is required to guide pointing than gaze) are both plausible.

The studies discussed so far provide evidence that two-year-old children show a clear gravity bias in the tubes task, especially according to the search-based measure typically used. This bias is resistant to counterevidence—it persists across repeated trials, even if there is only one tube and the apparatus remains configured in the same way—and is evident until a later age if more tubes are intertwined. Eventual success in the task at around four years of age seems to depend on (a) being able to understand how the tube constrains a falling object’s movement; and (b) possessing sufficient inhibitory control skills to suppress inappropriate responding on the basis of a naïve gravity bias.

In the next section we present comparative work with non-human animals that has aimed to investigate whether a gravity bias might be shared across species, or conversely, could be unique to human children. Do other species also exhibit a comparable error when searching for objects invisibly displaced by gravity?

Non-human animal studies

Might a naïve theory about the trajectory of falling objects be unique to humans, or do other species also exhibit a gravity error when searching for invisibly displaced dropped objects? The ability to track and locate objects that have moved out of sight is an ecologically relevant problem for many species (Hauser, Williams, Kralik, & Moskovitz, 2001). Terrestrial and arboreal species in particular—especially those that forage for food that falls to the ground—frequently experience the effects of gravity on unsupported objects. It is therefore reasonable to expect that they, like children, might have a naïve gravity bias, and indeed it has been claimed that non-human species including monkeys (Hood et al., 1999) and dogs (Osthaus et al., 2003) do have a gravity bias.

The tubes task was designed for use with pre-verbal children, and its simplicity makes it suitable for conducting comparative studies with diverse non-human species. It is possible to implement the task without using verbal instructions, with relatively little pre-training, and the motor demands are minimal. Several studies have adapted the tubes task—mainly using the single diagonal tube task of Hood’s (1995) Experiment 4—to examine performance in non-human animals and how it compares to that of human children. The aim of these studies has been to shed light on the mechanisms underpinning the gravity bias and enhance our knowledge of the nature and origins of theory-like physical reasoning and cognitive mechanisms more generally. We discuss these studies in the following sections.

Non-human primate studies

The majority of non-human studies using the tubes task have focussed on our closest relatives—the non-human primates. In the first non-human study, nine cotton-top tamarins (*Sanguinus oedipus oedipus*) were presented with the diagonal tube task (Hood et al., 1999). Seven out of nine individuals searched the gravity location in their first trial, providing evidence for an initial gravity bias in this species (Table 1).

Table 1. Performance of different species in the diagonal tube task

Species	Trial 1 gravity searches	Trial 2 gravity searches	Overall gravity searches^	Reference
2-year-old children (*Homo sapiens*)	9/10	8/10	62%	Hood (1995), Exp. 4 pre-test
Great apes (*Pan troglodytes, Pan paniscus, Gorilla gorilla, Pongo pygmaeus*)	8/22	+	~20%	Cacchione & Call (2010), Exp. 2 silent condition
Cotton-top tamarins (*Sanguinus oedipus oedipus*)	7/9	2/9	39%	Hood et al. (1999)
Common marmoset (*Callithrix jacchus*)	4/7	+	~30%	Cacchione & Burkhart (2012)
Domestic dog (*Canis familiaris*)	8/16	6/16	19%	Osthaus et al. (2003), Exp. 1 diagonal condition
Domestic dog (*Canis familiaris*)	5/16	3/16	16%	Tecwyn & Buchsbaum (in press), Exp. 1a

^ For studies involving multiple test sessions, performance in session 1 is reported; + indicates data unavailable

However, in their second trial only 2/9 monkeys searched the gravity location, and across all trials only 39% of searches were directed at the gravity location. Therefore, while this study provides the most compelling evidence to date that a non-human species' search behavior might initially be guided by gravity, this pattern of dramatically reduced searching of the gravity location in trial 2 does not fit the 'challenging to overcome' criterion proposed by Hood (1998) when describing the gravity bias he observed in young children.

Additionally, tamarins that had previously participated in a horizontal version of the diagonal tube task did not exhibit a gravity bias when subsequently presented with the vertical version, even in their first trial (Hauser et al., 2001). This suggests that any gravity bias may not be very robust in this species, and can be overcome with experience of food moving through tubes in a non-gravity-based context. In contrast, 2-year-old children who participated in a transparent version of the vertical tubes task (and were able to solve it) still exhibited a gravity bias when they were tested with the opaque version immediately afterwards (Hood, 1995).

Findings from subsequent studies with monkeys and apes further suggest that the gravity bias might in fact not be a phylogenetically widespread phenomenon, even within primates. Only 4/7 common marmosets (*Callithrix jacchus*) searched the gravity location in their first trial of the diagonal tube task, and only 39% of all trials in session 1 of the study were directed to the gravity location (Cacchione & Burkhart, 2012; Table 1). A looking-time version of the task showed that, similarly to young children directing their gaze towards the correct end location (Lee & Kuhlmeier, 2013), marmosets looked longer when the object was revealed to have ended up in the impossible gravity location, compared with when it ended up in the correct location (Cacchione & Burkart, 2012), demonstrating a lack of a gravity bias according to this implicit measure.

Two studies have used versions of the tubes task to investigate whether non-human great apes have a gravity bias. A study by Cacchione and Call (2010) presented all four non-human great ape species with the standard diagonal tube task. Apes searched randomly in trial 1, but more individuals searched the correct location than the gravity location, and the overall number of gravity searches in session 1 of the experiment was low at around 20% (Cacchione & Call, 2010; Table 1). However, when apes did make an error, they were significantly more likely to search the gravity location than the middle location, suggesting that apes may indeed hold naïve beliefs about gravity, but they are usually able to suppress acting on the basis of this belief when it is inappropriate. On the basis of these results, it has been suggested that great apes might be less susceptible than monkeys and 2-year-old children to making gravity errors because of their superior inhibitory skills—it is not necessarily the case that apes do not have naïve beliefs about the influence of gravity on unsupported objects, it could just be that they are better able to suppress acting on the basis of this bias (Cacchione & Call, 2010).

In addition, several of the apes in this study had previously completed an ‘acoustic’ version of the task, in which they were able to hear the reward rolling down the tube, thus providing information regarding the causal mechanism of the tube. Since causal mechanism information improves children’s performance, it is difficult to know how this experience might have influenced apes’ subsequent performance in the traditional ‘silent’ version of the diagonal tube task, rendering direct comparisons of the ape data with data from other species problematic.

The findings of an earlier study by Tomonaga, Imura, Mizuno, & Tanaka (2007) supports the possibility that great apes might have a gravity bias that they are able to inhibit. Tomonaga and colleagues presented immature and adult chimpanzees (*Pan troglodytes*) with a task involving two crossed tubes, but rather than searching for the object after it had been dropped down the tube, chimpanzees had to predict where the object would appear by putting their hand at the bottom of one of the tubes before it was released. The authors reported that chimpanzees in both age groups consistently selected the gravity location directly beneath where the reward was held, providing some evidence that chimpanzees’ reasoning about the trajectory of falling objects might be influenced by gravity. Based on the results of these two studies it is possible that apes are able to solve the single diagonal tube task, but reveal a gravity bias when the task is more complex because more tubes are intertwined, which is known to increase children’s preference for the gravity location (Hood, 1995; Lee & Kuhlmeier, 2013). However, given that there were other differences between tasks in addition to the number of tubes—two vs. three search locations; prediction- vs. search-based measure—it is difficult to compare these findings directly with the other non-human studies discussed in this section.

Overall, there appears to be mixed evidence for gravity biases in non-human primates. While there is evidence that the search behavior of all of the species tested to date is influenced by gravity to some extent—tamarins searched the gravity location in trial 1 (Hood et al., 1999); marmosets were more likely to search the gravity than the middle location when they erred (Cacchione & Burkhart, 2012), as were apes with a single tube (Cacchione & Call, 2010); and chimps with two crossed tubes showed the most compelling gravity bias (Tomonaga et al., 2007)—whether the performance of any of these species is indicative of a naïve theory of gravity comparable to young children's is less clear.

Domestic dog studies

To date, the only non-primate species to have been presented with the diagonal tube task is the domestic dog (*Canis familiaris*; Osthaus, Slater, & Lea, 2003; Tecwyn & Buchsbaum, in press). Osthaus and colleagues (2003) found that 8/16 dogs searched the gravity location in trial 1 and this proportion decreased steadily across repeated trials (Table 1). Despite this weak evidence for an initial gravity bias in dogs, this paper has often been interpreted in the literature as demonstrating that dogs have a robust gravity bias—at least initially—in the diagonal tube task (e.g., Bascandziev & Harris, 2011; Cacchione & Call, 2010; Joh et al., 2011; Tomonaga et al., 2007). A recent study that replicated and extended the diagonal tube task with dogs also found no evidence that this species searches on the basis of a naïve gravity bias, either in their very first trial (5/16 gravity searches), or across all trials (16% of searches directed to the gravity location; Tecwyn & Buchsbaum, in press; Table 1). Dogs in this study also did not search correctly immediately, and in some modified versions of the task they failed to learn to search correctly even across multiple trials, which suggests that they may be particularly poor at understanding the tube's causal mechanism.

Conclusion

Two-year-old children show a compelling gravity bias in even simple versions of the tubes task, and this bias is also seen in children up to around 3.5 years of age when multiple tubes are intertwined. This finding is robust and has been replicated across multiple studies. The evidence that any non-human animals possess a gravity bias—at least to a comparable extent to young children—is less conclusive. Despite being widely described as having a gravity bias across the literature, there is currently little evidence for a gravity bias in dogs. It is possible that the search behavior of some monkey species is initially guided by gravity (e.g. cotton-top tamarins; Hood, Hauser, Anderson, & Santos, 1999), but there is little evidence that this gravity-biased search persists across multiple trials, and thus an important criterion of a naïve gravity bias according to Hood (1995; 1998)—resistance to counterevidence—is not met. The most suggestive evidence of a gravity bias was found in the great apes, who may show a gravity bias when multiple tubes are intertwined, similar to 3-year-old children. At present, whether and to what extent any non-human species share young children's persistent gravity bias remains an open question that warrants further investigation.

Current limitations and future directions

Several factors limit the extent to which it is possible to make valid comparisons between different species. Given that there is evidence that the number of tubes influences children's performance in the task and the extent to which they exhibit a gravity bias (Hood et al., 1995; Lee & Kuhlmeier, 2013; Palmquist et al., 2018), this makes meaningful comparisons between existing child and non-human animal studies challenging. It is possible that if the apparatus was more complex (i.e. more tubes were intertwined, as in the majority of developmental studies) non-human animals would also be more susceptible to a gravity bias—and indeed there is some evidence from chimpanzees to suggest that this is the case (Tomonaga et al., 2007). Several other methodological inconsistencies between studies with children and non-human animals (and indeed between different non-human animal studies) render valid cross-species comparisons tricky, including: whether the tube configuration is variable or fixed between trials; differences in pre-training procedures; differences in the number of test trials presented; variation with regards to prior experience with related tasks; and a lack of availability of trial-by-trial data.

Future work should address these issues by replicating the existing non-human studies with larger samples, and also by systematically manipulating the number of tubes in the apparatus to see if/whether this influences the strength of the gravity bias. Extending the paradigm to additional species that are known to differ with respect to their causal reasoning abilities, inhibitory skills, and ecology in terms of the extent to which they have experience of the effect of gravity on unsupported objects, could be particularly valuable for improving our understanding of the mechanisms underpinning gravity-biased vs. successful performance in the tubes task. A developmental comparative approach that examines performance in both immature and mature individuals across species would enable us to better understand the evolutionary origins of naïve beliefs about gravity.

Cross-References

Comparative cognition; Folk physics; Invisible displacement

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