Preschoolers search longer when there is more information to be gained

Azzurra Ruggeri*

Max Planck Research Group iSearch, Max Planck Institute for Human Development,

Department of Cognitive Science, Central European University, Vienna, and

School of Education, Technical University, Munich

Oana Stanciu

Department of Cognitive Science, Central European University, Vienna

Madeline Pelz

Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology, Cambridge

Alison Gopnik

Department of Psychology, University of California, Berkeley

Eric Schulz

Max Planck Research Group Computational Principles of Intelligence,

Max Planck Institute for Biological Cybernetics, Tübingen

Author Note

*Correspondence should be addressed to Azzurra Ruggeri, Max Planck Institute for Human Development, Lentzeallee, 94, 14195 Berlin, Germany. Email: ruggeri@mpib-berlin.mpg.de

Conflict of interest statement

The authors have no conflicts of interest to disclose.

Data statement

All data and code to reproduce the results reported in this article can be found on github: `https://github.com/ericschulz/doors`

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Research highlights

- Across three studies, we tested whether information gain itself acts as an internal reward and suffices to motivate preschoolers' actions.
- We measured preschoolers' persistence when searching for an object behind a series of doors, manipulating the uncertainty about which specific object was hidden.
- We found that preschoolers were more persistent when there was higher uncertainty, and therefore more information to be gained with each action.
- Our results highlight the importance of research on artificial intelligence to invest in curiosity-driven algorithms.

Abstract

What drives children to explore and learn when external rewards are uncertain or absent? Across three studies, we tested whether information gain itself acts as an internal reward and suffices to motivate children's actions. We measured 24- to 56-month-olds' persistence in a game where they had to search for an object (animal or toy), which they never find, hidden behind a series of doors, manipulating the degree of uncertainty about *which specific object* was hidden. We found that children were more persistent in their search when there was higher uncertainty, and therefore more information to be gained with each action, highlighting the importance of research on artificial intelligence to invest in curiosity-driven algorithms.

Keywords: Active Learning, Information Gain, Developmental Psychology, Hypothesis Testing

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Introduction

One of the greatest challenges for artificial intelligence is designing agents that behave adaptively when there are uncertain, sparse, or no rewards. Psychologists, computer scientists and roboticists have been keen to point out that one–and perhaps the only–way to approach such complex learning problems is to build simple algorithms that grow into sophisticated adaptive agents, similar to how children grow into adults. In particular, they suggest that, in such uncertain and dynamic scenarios, "curiosity-based" systems may do better than standard reinforcement learning methods (Pathak, Agrawal, Efros, & Darrell, 2017; Schmidhuber, 2010).

Loewenstein's (1994) prominent "information-gap" theory suggests that human curiosity is driven by an individual identifying a gap in their knowledge, which then motivates them to explore and seek out additional information in order to close that gap. This theory has laid the foundation for many behavioral studies in psychology, as well as research in artificial intelligence, with many curiosity-based systems relying on the idea that quantitative increases in information gain are themselves rewarding and motivate actions (Loewenstein, 1994).

The information-gap theory has also had a widespread influence on the study of curiosity in children. Previous research has shown that even at 11 months of age, infants prefer to explore surprising events (Stahl & Feigenson, 2015). This attentional capture can be characterized in terms of informational surprise (Kidd, Piantadosi, & Aslin, 2012), with infants showing the most attention to situations of intermediate visual complexity, supposedly to avoid wasting cognitive resources trying to process overly simple or overly complex events (Schmidhuber, 2010). Along these lines, a growing body of work has shown that children are more likely to explore when presented with confounded (L. E. Schulz & Bonawitz, 2007) or unexpected evidence (Bonawitz, van Schijndel, Friel, & Schulz, 2012), that they seek out uncertainty reduction more eagerly than adults (Meder, Wu, Schulz, & Ruggeri, 2020; E. Schulz, Wu, Ruggeri, & Meder, 2019), and are sensitive to the potential information gain of different actions (Jirout & Klahr, 2012; Ruggeri, Sim, & Xu, 2017; Ruggeri, Swaboda, Sim, & Gopnik, 2019).

Maw and Maw (1964) put forth a definition of curiosity in young children that highlighted the extent to which children are interested in gaining knowledge about themselves and their environments, seek new experiences by choosing to explore novel or confusing things, and persist in this exploration until they gain that knowledge. Much of the research that followed has focused on behavioral tasks that assessed children's spontaneous exploration of objects, as well as those that used measures of exploratory preference between different scenarios that differed in their potential information gain (see Jirout and Klahr (2012) for a detailed review).

But one important aspect of curiosity that Maw and Maw (1964) laid out in their definition is not addressed by studies that rely on preferential exploration - specifically how curiosity drives persistence on a single task rather than how it drives children to choose to explore one object or environment over the other. Persistence is a meaningful predictor of academic outcomes and is affected by features of the target of children's attention, as well as by social factors like parental praise and modeling (Leonard, Lee, & Schulz, 2017). The ability to identify and stick with a challenge, often also described as "grit," is predictive of success in both children and adults beyond intelligence or specific skill (Duckworth, Peterson, Matthews, & Kelly, 2007). Despite our understanding of the importance of persistence, to our knowledge, there has not been research specifically addressing how differences in potential information gain might systematically affect young children's persistence in exploration.

Classic work in reinforcement learning shows that agents are more likely to act and act more persistently when pursuing greater rewards. Will preschoolers be more persistent in situations where there is more *information* at stake? Previous work has largely focused on the role of extrinsic reward structures, so it is unclear if expected information gain alone can serve as an intrinsic reward, strong enough to drive children to persist in their exploration? In the present studies, we measured how long toddlers and preschoolers, aged 2 to 4 years old, were willing to keep searching for something they never found. Children were told that they had to find an object (animal or toy) hiding behind one of a virtually infinite series of doors, sequentially presented on a screen (see Fig. 1). Across three studies, we manipulated the degree of uncertainty as to which specific object they were searching for, and measured the effects on children's search persistence.

In Study 1, we compared a condition where children were told which animal they were looking for (*1-animal* condition; e.g., find Sam, the lion) to a condition where they did not know which of eight possible animals was hiding (*8-animals* condition; i.e., find Sam, which could be a lion, an elephant, a hippo, a zebra, a crocodile, a bird, a turtle, or a whale, see Fig. 1). This subtle difference in the task instructions was enough to crucially impact the information gain (IG) of the same action (i.e., opening a door) across the different conditions. Indeed, intuitively, in the 8-animals condition, compared to the 1-animal condition, opening a door offered the opportunity to discover not only the location of the hidden animal, but also its identity. Formally, the information gained about the animal when opening one door in the 1-animal condition was IG=$-\log(1) = 0$, whereas in the 8-animals condition it was IG=$-\log(1/8) = 3$. In Study 2, we replicated and extended the results of Study 1, testing an independent sample of 2- to 4-year-olds on an even more subtle manipulation: Instead of contrasting a certain (1-animal) against an uncertain condition (8-animals), we varied the *degree* of uncertainty between conditions, comparing the same 8-animals condition from Study 1 with a 2-animals condition, where children did not know which of *two* possible animals was hiding (IG=$-\log(1/2) = 1$; see Fig. 1). In this sense, children in this condition still gained some additional information about the animal's identity upon searching, but to a lesser extent than in the 8-animals condition. In Study 3, we replicated and extended our investigation further by presenting an independent sample of 3- to 4-year-olds with the 1-animal and the 8-animals condition from Study 1, this time in a within-subjects design (order counterbalanced). This manipulation was crucial to capture to what extent the effects observed in Study 1 and 2 are stable and reliable at the individual level.

Study 1

Methods

Participants. We recruited 49 young children (range: 24 to 52 months, 26 female, $M_{\text{age}} = 38.06$; SD=7.77) from preschools and museums in the [blind for review]. Sample size in all studies was determined by conducting an a-priori power calculation based on the planned t-test comparison of number of doors opened in the two conditions (Cohen's d = 0.8, 80% power). Nine additional participants were excluded because they were distracted (n=4), could not operate the tablet (n=1), parental intervention (n=2), technical difficulties (n=1) or because the child did not understand English (n=1). Informed consent was obtained from the parents of all participating children. Ethics approval for Study 1 was obtained by the ethical review board of the [blind for review] (protocol: [blind for review]).

Design and Materials. In this game, children were told to look for Sam, i.e., an animal hidden behind one of the doors. The experiment used a between-subjects design, where participants were assigned to either the 1-animal or the 8-animals condition. In the 1-animal condition, they were shown which specific animal Sam was, randomly assigned for each child to be either a lion, an elephant, a hippo, a zebra, a crocodile, a bird, a turtle, or a whale. In the 8-animals condition, children were told that Sam could have been one of the eight animals displayed on the screen, but were not told which one. The task was presented on a tablet, which presented a virtually infinite series of closed doors, displayed one at the time. After touching a door on the screen, it would open to reveal what was behind it. Afterwards, the next closed door would be displayed. The procedure and stimuli of Study 1 are illustrated in Fig. 1.

Crucially, in both conditions, the animal would never appear, i.e. there was nothing behind any of the doors. The session was ended when children gave up searching (e.g., left the table; see below) or if they had not given up searching after 4 minutes. At the end of the session, the experimenter encouraged children to open one more door, at which point they would actually find Sam.

Results

For all studies, we report both frequentist and Bayesian tests. Frequentist tests are presented alongside their effect sizes, i.e. Cohen's *d*. Bayesian statistics are expressed as Bayes factors (*BF*s), quantifying the likelihood of the data under the alternative compared to the null hypothesis. We apply Bayesian t-test for comparing independent groups, using a Jeffreys-Zellner-Siow prior with its scale set to $\sqrt{2}/2$. We perform Bayesian linear regression with a normal prior on the weights $\hat{\beta} \sim \mathcal{N}(0, 100)$.

We examined three indicators of children's persistence: the number of doors they opened before they stopped searching, the latency from the start of the experiment to the first time they showed signs of giving up the search (i.e., leaving their chair, looking away or not opening the currently presented door for longer than 10 seconds, talking to their caregiver, verbally expressing their frustration for not having found Sam just yet), and the proportion of children who kept opening doors until the predetermined time limit of 4 minutes. All measures converged in showing that children were more persistent in their search when the information gain of their actions was higher.

In particular, we found that children in the 8-animals condition, compared to children in the 1-animal condition, opened more doors on average (24.83 vs. 16.16 doors; Student's $t(47) = 3.43$, $p = .001$, Cohen's $d = 0.98$, Bayes Factor $BF = 50.8$) and searched for a longer time (133.22 vs. 91.31 seconds; $t(47) = 3.46$, $p < .001$, $d = 0.99$, $BF = 55.1$), as can be seen in Fig. 2, top and mid row of the left panel. Moreover, whereas only 7 out of 24 children reached the time limit in the 1-animal condition, 20 out of 25 did so in the 8-animals condition, see Fig. 2, bottom row of the left panel. Thus, significantly more children endured search until the end of the game in the 8-animals compared to the 1-animal condition (0.71 vs. 0.20, $\chi^2(1, N = 49) = 12.79$, $p < .001$, $BF = 207.9$). Finally, we regressed participants' age in months and their condition onto the number of opened doors in a Bayesian linear regression, extracting the posterior estimates of both variables' effects onto the number of doors opened. This analysis showed that children opened more doors overall the older they were ($\hat{\beta} = 3.867$, 95%HPD: $[1.69, 6.10]$), but that the effect of condition persisted even when controlling for age ($\hat{\beta} = 10.02$, 95%HPD: $[5.63, 14.33]$). We found similar results when regressing onto latency.

Study 2

Methods

Participants. We recruited 44 young children (range: 26 to 56 months, 17 female, $M_{\text{age}} = 37.41$; SD=7.56) from the Zoo in [blind for review]. Fourteen additional participants were excluded because they were distracted (n=2), could not operate the tablet (n=1), parental intervention (n=2), technical difficulties (n=7) or the child did not understand English (n=2).

Informed consent was obtained from the parents of all participating children. Ethics approval for Study 2 and Study 3 was obtained by the ethical review board of the Max Planck Institute for [blind for review].

Design and Materials. Study 2 used exactly the same stimuli, and implemented the same procedure and design of Study 1, with one difference only: Instead of comparing an unknown-animal (8-animals) condition to a known-animal (1-animal) condition, we compared two unknown-animal conditions, in which children were told that the animal hiding could have been one of two (2-animals condition) or eight different animals (8-animals condition), but were not told which one. Note that the 8-animals condition is identical as in Study 1. The procedure and stimuli of Study 2 are illustrated in Fig. 1.

Results

As in Study 1, all measures converged to indicate that children were more persistent in their search when the information gain of their actions was higher, in the 8-animals compared to the 2-animals condition: They opened more doors on average (32.2 vs. 19.1 doors; $t(42) = 3.93$, $p < .001$, $d = 1.11$, $BF = 89.5$) and searched longer before showing signs of leaving (124.1 vs. 80.6 seconds; $t(32) = 2.49$, $p = .018$, $d = 0.86$, $BF = 6.36$), see Fig. 2, mid panel. Moreover, whereas 13 out of 22 participants reached the time limit in the 2-animals condition, 20 out of 24 did so in the 8-animals condition ($\chi^2(1, N = 46) = 4.37$, $p = .036$, $BF = 5.67$). Finally, as in Study 1, regressing children's age in months and their condition onto the number of opened doors showed that children opened more doors the older they were ($\hat{\beta} = 0.618$, 95%HPD: $[0.15, 1.08]$), and confirmed that the effect of condition persisted even when controlling for age ($\hat{\beta} = 10.50$, 95%HPD: $[3.52, 17.51]$).

Study 3

Methods

Participants. We recruited 24 young children (range: 37 to 48 months, 15 female, $M_{\text{age}} = 41.50$; SD=3.12) from the participants database of the [blind for review]. Six additional participants were excluded because of technical difficulties (n=3), or because they did not want to participate anymore (n=3). Informed consent was obtained from the parents of all participating children.

Design and Materials. In Study 3, we implemented three crucial changes to the main paradigm: First, we presented children with both conditions in a within-subjects design (order counterbalanced). To do that, we used two different sets of objects and cover stories (animals, as in Study 1 and 2, and toys, in counterbalanced assignment to conditions). Second, we implemented a small but crucial change to the procedure of the *1-animal/toy* condition, eliminating a potential confound from the previous studies: we showed children at the beginning *all eight* animals/toys, before telling them which one they were looking for. In this way, we could make sure that children understood the crucial difference between conditions, and that the observed differences could not be attributed to them simply being initially exposed to more objects in the *8-animals/toys condition*. Third, because of the restrictions related to the COVID-19 pandemic, the study was administered online through a video-conferencing platform. For this reason, children would have to say "Open!" ["Auf!" in German] to open the doors, instead of touching the doors on the screen. Also, as it was easier for children to get distracted in the online administration of the task, the session was ended if the child had not given up searching after 3 minutes, instead of 4 minutes as in the previous studies. The procedure was not altered in any other way. The procedure and stimuli of Study 3 are illustrated in Fig. 1.

Results

As in Study 1 and 2, all measures converged to indicate that children were more persistent in their search when the information gain of their actions was higher, in the 8-animals/toys compared to the 1-animal/toy condition (see Fig. 2, right panel): they opened more doors (25.5 vs. 20.2 doors; $t(23) = 3.44$, $p = .002$, $d = 0.70$, $BF = 34.91$) and searched longer before showing signs of leaving (88.35 vs. 63.7 seconds; $t(23) = 2.96$, $p = .007$, $d = 0.60$, $BF = 13.01$). Moreover, children reached the time limit in the 8-animals/toys condition more often as compared to the 1-animal/toy condition (20 out of 24 vs. 13 out of 22; $\chi^2(1) = 6.8275$, $p = .009$, $BF = 124.91$). Finally, regressing children's age in months and their condition onto the number of opened doors showed no effect of age ($\hat{\beta} = 0.20$, 95%HPD: $[-0.82, 1.22]$), but confirmed that the effect of condition again persisted when controlling for age ($\hat{\beta} = 5.29$, 95%HPD: $[2.27, 8.31]$).

Discussion

A challenging problem for intelligent systems is how to behave in scenarios with sparsely occurring, uncertain or no rewards. Yet, already very young children successfully cope with this challenge successfully. How do they accomplish this?

We studied children's persistence in a search task without rewards, manipulating across three studies the expected information gain of the same search action. Overall, our results robustly suggest that toddlers and preschoolers were more persistent in their search when there was more information to be gained. Note that this was true when contrasting *whether* the same action would yield additional information gain or not (Study 1), as well as when manipulating the *amount* of additional information gained (Study 2). Crucially, we obtained exactly the same results when conditions were manipulated within subjects (Study 3), indicating that the observed effects are robust and stable, even at the individual level. Thus, our work suggests that information gain is enough to drive young children's exploration, as an intrinsic reward, even in the absence of any other explicit rewards or observed outcomes.

It is possible that information gain modulated perseverance on the search task indirectly by causing differences in the children's level of (emotional) arousal, their anticipatory excitement and overall engagement with and enjoyment of the task. Indeed, Schmidhuber (2010) proposed a formal conceptualization of "fun" along similar theoretical lines (i.e., fun measured by the extent to which one's model of the world improves with each step). It is certainly impossible to tease apart the contribution of direct and indirect effects of information gain on search perseverance with the current design (and likely with most behavioral designs). However, Study 3 partially addressed this concern by presenting the full set of animals in both conditions, and, therefore, minimized potential differences in arousal and other related factors, and still generated the same pattern of results. Thus, while remaining agnostic about the causal mechanism (and hoping that children do derive extra enjoyment from tasks with a greater potential for learning), we believe that we have strong evidence that information gain induces differences in young children's propensity to persevere when searching for information.

One potential limitation of the design is that strong individual preferences for a stimulus or a subsets of stimuli (e.g., children having a strong interest in elephants) could potentially confound the effects of the experimental manipulation. Namely, since by chance the preferred animal is more likely to be found in the 8-animal condition than the 1-animal/2-animals condition, and assuming that a strong preference would lead to increased search for the preferred animal, we would expect longer search times in the 8-animals condition. However, we believe it is unlikely that children formed such strong preferences based on novel and highly similar stimuli.

All in all, these findings consolidate our understanding of children's motivation to learn and explore, and have strong implications for both developmental psychology and artificial intelligence. From the perspective of developmental psychology, the results are consistent with a theory of children's exploration and learning that is driven by uncertainty reduction. From the perspective of artificial intelligence, our findings lend further support to the idea that to build machines that learn like children, one should build curiosity-based systems, designing algorithms that are motivated by the underlying expected information gain of their actions.

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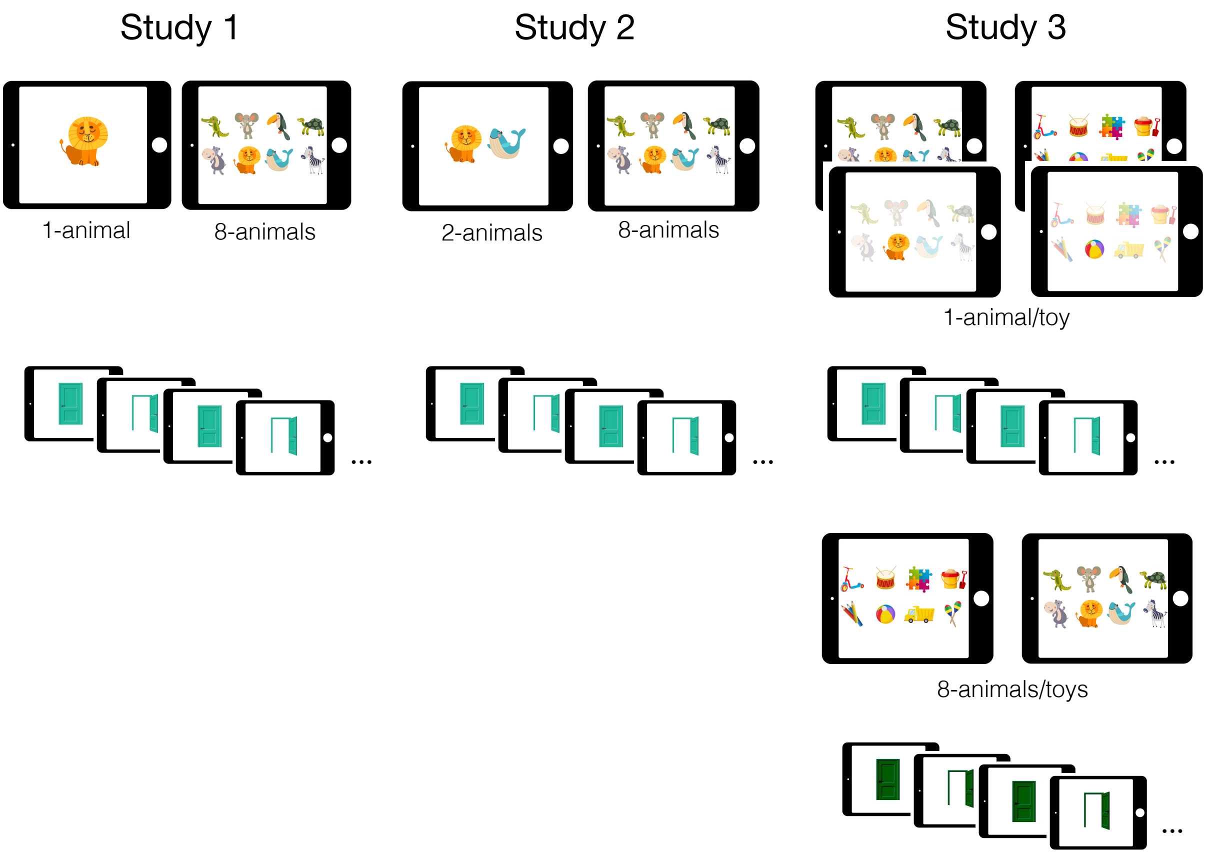

Figure 1. Illustration of the stimuli and procedure used in Study 1 (left), Study 2 (middle) and Study 3 (right). Whereas in Study 1 and 2 conditions were assigned between subjects, in Study 3 they were manipulated within subjects (order of conditions counterbalanced; sets of animals and toys stimuli in counterbalanced assignment to conditions).

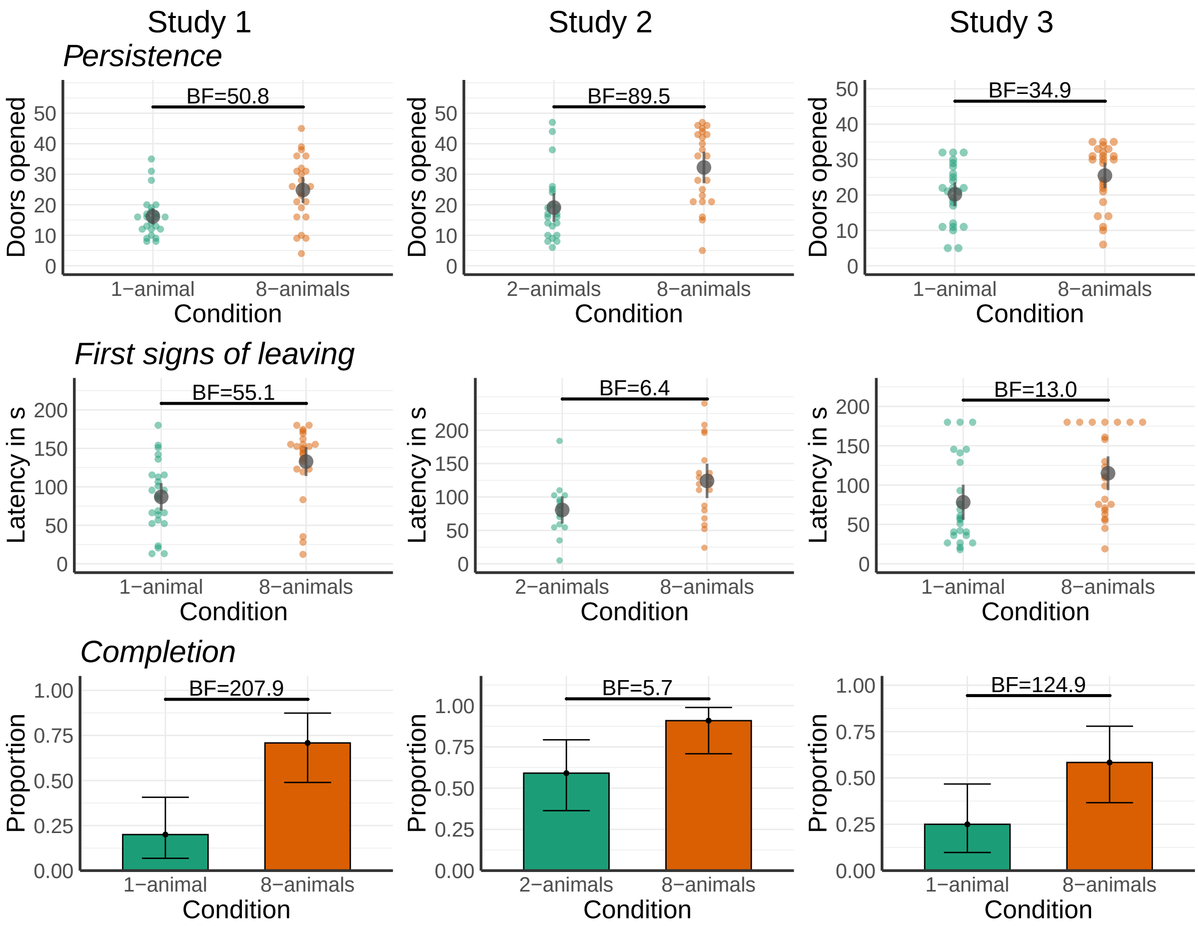

Figure 2. Results of Study 1 (left), Study 2 (middle) and Study 3 (right). Top row: Total number of doors opened by condition. Mid row: First signs of leaving, measured as the latency in seconds from the beginning of the search to the point at which children first signaled that they wanted to give up searching. Dots indicate individual participants. Black dot and error bars indicate the group mean and the 95% confidence intervals. Bottom row: Proportion of children searching until the predetermined time limit. Error bars represent the 95% confidence interval of a binomial distribution. All figures also show the resulting Bayes Factor when comparing the two conditions.