Abstract

Information gaps seem to play a central role in information-seeking, decision-making, and learning. As a result, the term ‘information gap’ has widespread appeal and utility across multiple disciplines. However, there is no agreed-upon meaning for the term ‘information gap’, leaving it open to the scientific interpretation. Here, we consider ways that ‘information gap’ has been conceptualized. While multiple uses of the term ‘information gap’ point can be problematic to the literature, they also indicate many relevant but underappreciated dimensions of information gaps.

Information Gap Review Outline

In 1994, George Loewenstein highlighted the importance of information gaps — gaps in knowledge — on curiosity. Empirical work suggests that information gaps play a central role in information-seeking, decision-making, and learning. Loewenstein (1994) has been cited over 1500 times across fields such as economics, behavioral economics, social and personality psychology, psychology, medical education, human-computer interaction, computer science, user experience design, marketing, addiction, tourism, political science, neuroscience, computational neuroscience, language learning, pragmatics, and pedagogy. But what exactly *is* an “information gap”? Currently, there is no clear consensus on how this concept should be formally defined. Instead, researchers---even two within the same field---may use that same term to refer to two entirely different dimensions of knowledge uncertainty. For example, ‘information gap’ may refer to a learner’s estimate of their uncertainty (e.g., Kang et al., xxxx) or the waiting time before a learner receives an anticipated piece of information (e.g., Noordeweir & van Dijk, 2015).

This lack of consensus about the meaning is problematic for the nascent field of curiosity for one fundamental reason: manuscripts which use two entirely different formalizations of the concept, at first glance, may appear to contradict each other when the results are in fact orthogonal. For example, ‘information gap’ may refer to entropy (e.g., Loewenstein xxx), surprisal (e.g., xx), a learner’s estimate of their epistemic uncertainty (e.g., Kang et al., xxx; Gruber et al., xxx), or ground-truth perceptual or epistemic uncertainty. This potential for apparent disagreement where there actually is no conflict threatens to stifle scientific progress. [MAYBE THAT IS TOO STRONG, WE CAN COME BACK LATER]

Be that as it may, this literature contributes to our understanding of what an ‘information gap’ can be. Collectively, this disparate literature (1) raises important theoretical questions about the meaning of the term ‘information gap’ and (2) leaves open areas for future research (re: underexplored dimensions).

Information gap - papers seem to contradict each other

But they use different definitions

Final position: we don't know what the underlying neural representations are, if these are the same thing and we need to be clear

Explain to someone 2 tricks

Powerpoint - skeleton

2 minute version

Write the shortest possible paper and expand as needed

Sunday morning

Many things can constitute an ‘information gap’, but information gaps are not all the same

Researchers have used many different dimensions of knowledge uncertainty as a proxy for an ‘information gap’. Each of these variables highlights some type of gap, but the source of uncertainty varies. For example, the source of uncertainty may be the learner. To that end, (1), (2), and (4) include the learner’s estimate of their uncertainty about some information. (3) is a proxy for uncertainty reduction. There is also knowledge uncertainty that can be estimated by more objective sources, such as exam outcomes (5). On the other hand, formal definitions of knowledge uncertainty / information gap typically focus on knowledge uncertainty related to about a causal/learning environment or system (6-9).

Collectively, these measures highlight multiple dimensions and sources for knowledge uncertainty. These measures differ in where the source of uncertainty is (e.g., estimated by the learner or a more objective estimate) and the degree to which the information gap pertains to an underlying system (e.g., knowledge system or causal/learning system/environment). For example, the answer to a trivia question may inform a knowledge system (e.g., if the trivia question is about a science phenomenon and you have an educational background to make sense of the question and answer) but it also may not (e.g., if the fact can be learned with little background knowledge).

Some measures derived from human estimates / performance:

1. the confidence of the learner about their knowledge (e.g., Kang et al. xxxx; Gruber et al xxxx)
2. the learner’s feeling of knowing an answer (e.g., Litman et al., xxxx)
3. The difference between a learner’s satisfaction for a trivia answer and their curiosity for the trivia answer (e.g., Marvin & Shohamy, 2016)
4. the difference between a learner’s assessment of how important a topic is and the learner’s confidence in their knowledge of the topic (e.g., Gentry et al., 2002)
5. Exam outcomes (e.g., Reio Jr., 2004)

In formal learning and decision making models, researchers have used the term ‘information gap’ to refer to:

1. Surprisal, an information-theoretic variable that refers to the amount of information gained by sampling one variable (e.g., Burda et al., xxxx)
2. Prediction error, the difference between a predicted outcome and the observed outcome (e.g., R-W model; Oudeyer & Kaplan, 2007)
3. Hypothesis space size, the number of hypotheses entertained at a given moment (e.g., Langford & Zhang, 2008)
4. Entropy, the average amount of information that is gained about a *system* by sampling one variable (Golman & Loewenstein, 2015)

**Using ‘information gap’ to refer to multiple sources of uncertainty causes problems**

While there may be similarities in the way that ‘information gap’ is operationally defined across studies (e.g., relying on a learner’s estimate of their certainty), generalizations *across* studies become problematic when there are differences in operational definitions. For example, in a study of middle-school and high-school student outcomes, Gentry et al. (2002) found that students with large information gaps were more likely to do worse on their first exam or assignment compared to students with small- to moderate-sized information gaps. In contrast, others have found that curiosity and subsequent learning or information seeking is greatest for questions that elicit *intermediate* confidence (Kang et al., 2009, Litman, Hutchins, & Russon, 2005; Gruber, Gelman, & Ranganath, 2014). These studies seem to contradict each other, but this is only because the operational definition of ‘information gap’ differs across these manuscripts. Gentry et al. (2002) define their information gap measure as the difference between a learner’s assessment of how important a topic is and the learner’s confidence in their knowledge of the topic. Gentry et al. (2002) separately consider the relationship between confidence and learning outcomes in their study and find better learning outcomes when learners have intermediate confidence, in line with the findings from Kang et al. (2009) and Gruber et al. (2014). Thus, while a learner’s retrospective confidence about knowing something may be related to measures that *include* confidence, other variables (in this case, the learner’s appraisal of how important a topic is) change the relationship between ‘information gap’ and other variables.

**Other things**

For the ML/Information Theory variables:

* What is the psychological plausibility of each of these measures?
* Role of feedback and metacognition in measures (across formal and informal theories) (e.g. prediction error vs. others)
* Scope of learning: learning about one thing or the underlying system

--Another thing, Loewenstein considers ‘information gaps’ to be a ‘reference-point phenomenon’, where a learner detects a gap up to a certain reference point. Across these measures, the reference point differs (e.g., the importance of the topic, complete certainty that one knows the information, complete certainty that one understands a causal system or learning environment, no more prediction errors, etc.).

-- also, the human estimates are mostly relative gap measures (except for the test results, but that’s kind of a weird gap measure because the knowledge set tested may be somewhat arbitrary given what the learner seeks to learn), but the ML measures are absolute.

**Metacognitive uncertainty may not reflect veridical informational uncertainty**

Human learning studies often use metacognitive estimates of certainty, such as confidence ratings from the learner (e.g., Kang et al., xxxx; Gruber et al., xxxx), or feeling-of-knowing (e.g., Litman et al., xxxx). In contrast, formal learning models make assumptions about ground-truth measures of certainty and information. A large body of work shows that a learner’s estimate of what they know (and what they don’t know) is not always aligned with reality (e.g., Wade & Kidd, 2019; Dunning & Kruger, xxx; Marti et al., xxxx; overconfidence literature). For example, a learner’s estimate of what they know (and don’t know) about trivia questions is not significantly predictive of what they actually know (or don’t know; Wade & Kidd, 2019). While learners are most curious about the things that they are maximally uncertain about, maximal uncertainty itself doesn’t predict better learning. Rather, curiosity and a more objective estimate of what the learner knows is predictive of better learning. [[need one more sentence here.. What we believe that we are measuring may be fundamentally different than what we are actually measuring, e.g., the pitfalls with introspection. However, a learner’s *perception* of informational uncertainty may be just as important -- if not more important -- than real-world informational uncertainty]]

The degree to which metacognitive abilities are calibrated to the real world differs across domains (e.g., Barthelmé & Mamassian, 2009; Martí, Mollica, Piantadosi, & Kidd, 2019), tasks (e.g., Schwartz & Metcalfe, 1992; Kelemen, Frost, & Weaver, 2000; Moore & Healy, 2008; Kornell, 2009; 2014), and individuals (e.g., Kruger & Dunning, 1999; Moore & Healy, 2008; Gilbert, 2015; but see Kelemen et al., 2000). Using metacognitive judgments as a proxy for information gaps tells us how the *learner’s* estimate of their knowledge plays a role in processes such as curiosity, information-seeking, and learning; whether or not this estimate is veridical is not always clear.

I think there is also something to be said about the use of prospective vs. retrospective judgments. For example, a confidence rating is a prospective judgment that you can access at the point of making a decision to seek information. However, if you use ‘satisfaction for the answer’ to calculate prediction error as a proxy for information gap, it taps into something that you don’t have access to at the point of making a decision. It may predict learning better than prospective judgments, but it is also categorically different from a prospective judgment in that it incorporates feedback (e.g., alignment of the answer with one’s current knowledge).

**Informational uncertainty may refer to a single piece of information or an entire system**

While human learning studies often focus on a single piece of information (e.g., the answer to a trivia question, resolving perceptual uncertainty by showing making a blurry image clear), formal learning models are often solving the problem of learning an entire system (e.g., physical environment; e.g., Oudeyer, Kaplan, Hafner, & Whyte, 2005; Oudeyer & Kaplan, 2006; 2009; or a virtual one; e.g., Burda, Edwards, Pathak, Storkey, Darrell, & Efros, 2018). System-wide information uncertainty reduction may require repeated actions or queries, longer learning periods, and hierarchical learning. On some level, both of these types of uncertainty impact each other. However, it remains to be seen whether the same processes that drive uncertainty reduction in trivia paradigms, for example, drive uncertainty reduction for more complex knowledge gaps in less familiar domains.

Conclusion

Currently, ‘information gap’ is used as a blanket term that refers to many different kinds of informational uncertainty. The term may refer to one or many bits of information; knowledge about a causal system, the specific answer to a question, or both; the perception of uncertainty or ground-truth uncertainty. Consequently, many studies are orthogonal to each other and cannot be directly compared. While this makes for a disparate scientific literature, these usages of the term ‘information gap’ highlight the importance of different kinds of informational uncertainty on learning processes and decision making behaviors. Information gaps are not all the same, and it is important to consider how dimensions of informational uncertainty contribute to the meaning of ‘information gap’, human behavior, and learning.

**Other things that seem to matter in regards to information uncertainty**

**Affect**

The decision to reduce one’s uncertainty seems to be influenced by the expected valence of the sought-after information. Previous work suggests that humans avoid information when it may require a change in beliefs, an undesired action, or unpleasant emotions (see Sweeny, Melnyk, Miller, & Shepperd, 2010). Inducing positive affect (e.g., awe) in the learner may increase a learner’s curiosity and information seeking. For example, awe-inducing science videos increase a learner’s curiosity for science (McPhetres, 2019). The valence of the information gap also seems to matter: humans are more likely to wait for — and are better at remembering — answers to trivia questions with positive valence compared to those with a neutral valence (Marvin & Shohamy, 2016). Finally, the wait time before an information gap resolves influences the affect of the learner which may have consequences for information seeking. Work by Noordeweir & van Dijk (2015) show changes in the experience of curiosity as a function of wait time: curiosity is less pleasant when there is a long wait time (e.g., 30 minutes) before gap resolution compared to when there is a short wait time (e.g., 1 minute). [[need sentence to wrap up]]

**Closure**

Work by Noordeweir and van Dijk suggests that the subjective experience of curiosity varies across waiting times (e.g., 1 minute vs. 30 minutes). It’s not clear how extending the time period to resolve the information gap might influence curiosity or learning of the missing information, for example. How the time to resolution influences the experience of curiosity is an important consideration for real-world information gaps, many of which take longer to resolve (and are more complicated) than a simple trivia question (e.g., learning a concept, topic, sport, trade, game, or language; reading a blog post, clickbait article, journal article, or book; watching a YouTube video, television episode, movie, or an entire series).

Many human studies on information gaps rely on easy-to-resolve gaps that are filled within seconds. For example, researchers may present trivia questions that are answered within seconds of presenting the question (e.g., Kang et al., xxxx; Litman et al., xxxx; Gruber et al., xxxx; Marvin & Shohamy, 2016; Wade & Kidd, 2019). Gruber et al. xxx used a screening phase, where participants first rated their curiosity for questions. In contrast, formal learning models may be solving the problem of learning an entire system (physical or virtual).

**Costs and Rewards**

With some exceptions, human studies with information gaps primarily involve small gaps that are easy to fill (e.g., trivia questions, image viewing). This paradigm may help explain human behavior over the thousands of small decisions they must make in a single day. However, there are other information gaps that require additional effort or may be inherently more rewarding to close. Primate work suggests that monkeys would forgo 20-33% of their daily water intake to get information about upcoming water reward outcomes sooner, even though this information did not have any effect on the reward outcome (Blanchard, Hayden, & Bromberg-Martin, 2014). This finding suggests that information may have value. This value may change across individuals (e.g., as in Blanchard et al., 2014) and it may also change across information. For example, knowing your result on an important exam (e.g., the SAT, GRE, MCAT, or LSAT) or a medical test (e.g., a pregnancy test) may have for far-reaching consequences than knowing which celebrity couple filed for divorce today. A pregnancy test result contains 1 bit of information (there are two possible outcomes), less information than finding out who filed for divorce today (there are more than two possible outcomes). There may be individual differences in the intrinsic and extrinsic motivation of a learner to acquire certain kinds of information.

The cost of filling an information gap may also vary from one gap to another. Some information gap paradigms use a waiting time (e.g., of 5-25 seconds; Kang et al., xxxx; others) or token system (e.g., Kang et et al., xxxx) to increase this cost. However, real-life information gaps may be inherently more expensive to close, whether it be through time (e.g., watching a documentary or movie for 1-2 hours) or money (e.g., paying money to expedite a delivery or get an exam score ahead of time). [[need a sentence here]]

**Insight vs. Incremental problems**

An information gap may resolve incrementally, with information being presented across time, or it may be resolved all at once. While many information gaps in human learning tasks are reduced immediately rather than incrementally (e.g., by revealing a trivia answer or the identity of a mystery prize), many information gaps in the real world involve incremental information gain (e.g., reading an article or watching a news segment). Little is known about how incremental changes to an information gap and properties associated with information gain (e.g., the rate of information; information theoretic entropy or surprisal) relate to processes such as curiosity, information seeking, and learning.

\*\* maybe refer back to nelson & narens, 1990 -- FOK is related to how close you are to solving an incremental problem, but not an insight problem.

Table 1. Examples of how ‘information gap’ is defined across domains and paradigms

| *Domain* | Task | Information Gap Measure | E.g. |
| --- | --- | --- | --- |
| *Psychology/*  *Neuroscience* | Trivia Questions | Learner’s Certainty | Kang et al.  Gruber et al. |
| *Psychology* | Trivia Questions | Feeling-of-Knowing | Litman et al. |
| *Psychology* | Trivia Questions | Prediction Error (Satisfaction - Curiosity) | Marvin & Shohamy (2016) |
| *Psychology/ Social* | View Video | Time before video (1 min or 30 min) | Noordeweir & van Dijk (2015) |
| *Psychology/ Neuroscience* | Image Recall | Blurry-Clear Related Condition (Blurry photo followed by clear photo of the same image) | Jepma, Verdonschot, Van Steenbergen, Rombouts, & Nieuwenhuis, (2012) |
| *Psychology* | Select a Reward | Mystery item (vs. a known item) | Van Dijk (xxxx) |
| *Psychology* | Learning (Model) | Prediction Error | Rescorla Wagner model (cite) |
| *Psychology/Information Processing* | Bandit Task | Hypothesis Space | Langford & Zhang (2008) |
| *Education* | Class performance (first exam/assignment outcome) | Importance - Confidence | Gentry et al. (2002) |
| *Education* | Class performance | Midterm and Final Grades + midterm question | Reio Jr. (2014) |
| *Economics/Behavioral* | (Model) | Entropy | Loewenstein (1994)  Golman &Loewenstein (2015) |
| *HCI* | Programming | Prediction Error | Wilson et al. (2003) |
| *HCI* | Task continuation on AMT | Scrambled photo vs. ordered; task-relevant narrative with missing parts + task-relevant question vs. just the task-relevant question | Law et al. (2016) |
| *HCI* | Task continuation on AMT | Scrambled photo vs. ordered; task-relevant narrative with missing parts + task-relevant question vs. just the task-relevant question | Law et al. (2016) |
| *AI/Robotics* | Active Learning | Prediction Error | Oudeyer & Kaplan (2007)  Cohn, Ghahramani, & Jordan (1996) |
| *Computer Science / Machine Learning* |  | Surprisal | Burda et al. |
| *Marketing* | Reward Choice | Mystery Gift (w/ varying amounts of information) vs. Known Gift | Goldsmith & Amir (2010) |
| *Marketing* | Purchase Motivation | Mystery discount revealed during check-out vs. before | Goldsmith & Amir (2010) |
| *Marketing* | Curiosity for Ad | Manipulated product identity (present/absent), details (present/absent), and tagline (present/absent) | Menon & Soman (2002) |

Other stuff (Celeste can disregard):

Here’s some stuff on marketing

In other domains, such as decision making / consumer behavior, we again find differences in the way ‘information gap’ is used. For example, it may refer to a mystery prize (vs. a known one; Goldsmith & Amir, 2010; van Dijk, xxxx); a mystery discount (vs. a known one; Goldsmith & Amir, 2010); or the amount of detail provided in an ad (e.g., Menon & Soman, 2002).

Van Dijk & Zeelenberg (2007) - preference for known prize (15 euros) over mystery one when given no information about the mystery prize (20/30), but the preference shifts when given some information (round/not round) about the mystery prize (21/30 or 20/30 preference for mystery prize, respectively).

Goldsmith & Amir (2010) -

This is a paragraph about how asking slightly different confidence question may elicit a different kind of metacognitive monitoring, leading to a different relationship between the question and curiosity or other kinds of processes:

We also find that there is a different relationship between curiosity and information gap depending on the wording of the confidence question. We asked participants “Do you think your guess is correct?” and “Do you think you know the correct answer?” -- people are more curious when they respond “yes” to “Do you think your guess is correct?” but “no” to “Do you think you know the correct answer?” Both of these questions probe whether there is a gap in the learner’s knowledge, but in distinctly separate ways. The focus of the question, for example, may lead individuals to focus on different aspects of their knowledge. A participant may respond “yes” to the first question only if they believe that the guess that they made is accurate. However, a participant may respond “yes” to the second question if they believe that they know the answer but are currently unable to produce it. The second question may be engaging participants in more metacognitive monitoring of their knowledge. [need another sentence here]