Psychonomic Bulletin & Review
2008, 15 (2), 284-289
doi: 10.3758/PBR.15.2.284

Frequency interpretation of ambiguous statistical information facilitates Bayesian reasoning

Gary L. Brase
Kansas State University, Manhattan, Kansas

The idea that naturally sampled frequencies facilitate performance in statistical reasoning tasks because they are a cognitively privileged representational format has been challenged by findings that similarly structured numbers presented as *chances* similarly facilitate performance, on the basis of the claim that these are technically single-event probabilities. A crucial opinion, however, is that of the research participants, who possibly interpret chances as de facto frequencies. A series of experiments here indicate that not only is performance improved by clearly presented natural frequencies, rather than chances phrasing, but also that participants who interpreted chances as frequencies, rather than as probabilities, were consistently better at statistical reasoning. This result was found across different variations of information presentation and across different populations.

Providing information in the form of naturally sampled frequencies facilitates performance in a number of judgment and decision-making tasks, including Bayesian reasoning problems (problems that involve obtaining the posterior probability of a hypothesis; see, e.g., Cosmides & Tooby, 1996; Gigerenzer & Hoffrage, 1995). These natural frequencies, specifically, are numerical frequencies (whole, countable numbers) presented within a natural-sampling framework (Kleiter, 1994; i.e., within a nonnormalized arrangement of nested categories). An example of such a task is the following:

> The applicants for admission to a prestigious university have to pass an entrance examination that involves both an oral test and a written test. Here is some information about the results of last year's examination: 5 out of 100 applicants were accepted. 3 of the 5 applicants who were accepted passed the oral test. However, 19 of the 95 applicants who were rejected also passed the oral test. Imagine 100 applicants are taking the entrance examination. Out of the _____ applicant(s) that will pass the oral test, _____ applicants will be accepted.

Note that the nonnormalized structure (i.e., all the numbers remain based on the initial group of 100, even when subgroups are discussed) effectively simplifies the actual computations needed to perform Bayesian reasoning tasks, because this set relations arrangement implicitly and automatically incorporates base rate information (as compared with using Bayes theorem with normalized data; Gigerenzer & Hoffrage, 1995).

Although all researchers agree that this presentation leads to improved performance, there is disagreement as to exactly why. The ecological rationality view is that the facilitation is due to the mesh between natural frequencies and the manner in which information is naturally acquired from the environment. This includes the serial acquisition of events as frequency counts, as well as the nested subset arrangement in which those counts are maintained. From this view, not only is the natural-sampling subset arrangement important, but facilitation is additionally due to frequencies being a cognitively privileged representational format (Cosmides & Tooby, 1996).

A contrasting *nested sets* view is that the use of frequency counts per se is superfluous to the computational simplification (e.g., Girotto & Gonzalez, 2001; Howson & Urbach, 1993; Sloman, Over, Slovak, & Stibel, 2003); frequencies are but one way to make the set relationships (i.e., nonnormalized natural-sampling structure) more explicit—which is the real source of all the facilitation. That is, rather than a specific affinity for natural frequencies, it is argued that the human mind has a more general capacity for appreciating set relations (implicitly, here, *nonnormalized* set relations, essentially a descriptive label for natural sampling; Brase & Barbey, 2006; Hoffrage, Gigerenzer, Krauss, & Martignon, 2002). This view can be traced back to observations by Tversky and Kahneman (1983) and maintains that frequencies are not a privileged representational format and are not facilitative in their own right.

There has, unfortunately, been confusion in this research area, with some studies using frequencies but failing to use a natural-sampling structure (a situation in which neither view predicts good performance; see, e.g., Girotto & Gonzalez, 2000) and other studies mixing frequencies and other formats (e.g., Evans, Handley, Perham, Over, & Thompson, 2000). A particularly interesting situation has developed on the basis of the work

G. L. Brase, gbrase@ksu.edu

of Girotto and Gonzalez (2001; see also Sloman et al., 2003), which—consistent with the nested sets view—credits all of the facilitation to the understanding of set relations. This research utilizes *chances* information, which are defined as probabilities (Girotto & Gonzalez, 2001, p. 252) and are explicitly distinguished from frequencies. (We must assume this to mean *single-event* probabilities, rather than the more general definition of probability that would also include frequencies.) This argument relies on two erroneous assumptions—one definitional and one methodological.

The fallacy of a definitional assumption that probabilities and frequencies are always separate dissociable entities has been pointed out by both ecological rationality proponents (Gigerenzer, 1994) and third-party authorities on probability theory (see discussions of probabilities as "Janus-faced" and open to different interpretations by objectivists, who favor objective frequency-of-event interpretations of probabilities, and by subjectivists, who favor single-event or subjective confidence interpretations of probabilities; see Atkinson & Peijnenburg, 1999; Von Mises, 1957). The methodological assumption follows from this definitional assumption; it is assumed that research participants are uniform and consistent in designating chances as nonfrequency probabilities. This assumption is critical here because the numerical information used to demonstrate the faciliatory effect of chances information is very similar to frequencies (e.g., "one individual has 12 out of 100 chances"). Although one can argue that these chances are single-event probabilities, one can equally argue that they are de facto natural frequencies (i.e., frequencies of potential events). The crucial opinion in this situation, however, is that of the research participants: How do participants interpret different numerical formats? The materials used by Girotto and Gonzalez (2001) are ambiguous in that they suggest both interpretations; they both invoke a single individual and yet consistently talk about multiple chances (using the plural form), which could be interpreted as frequencies of actual or hypothetical events.

EXPERIMENT 1

Experiment 1 was designed to evaluate how different numerical formats that are labeled as *chances* affect statistical reasoning and how different formats are actually perceived by the research participants. The use of the *chances* wording is intriguing precisely because it has been argued that it transcends typically intractable constraints (i.e., it is a probability, yet it can invoke both plural wording and natural-sampling structure). The key comparisons, then, are between tasks that vary only on what should be aspects crucial to performance. If the crucial aspect is only the existence of nonnormalized set relations, single-event probability interpretations of chances should not affect performance on tasks, so long as that nonnormalized set structure is in place. On the other hand, if it is the more specific use of frequencies (within such a structure) that is important—whether associated with the label of *chances* or not—correct Bayesian reasoning will be differentially elicited by de facto frequentist interpretations of chances information.

Method

Participants. The participants were 84 undergraduates at a regional university in Northern England (72 of them female and 12 male). All consented to participate in partial satisfaction of a class requirement. The average age was 21.6 years.

Materials and Procedure. Each participant was given a single sheet with some brief instructions and a Bayesian reasoning problem (adapted from Girotto & Gonzalez, 2001). An equal number of participants received one of three problems: (1) using the term "chances" and normalized percentage information, (2) using the term *chances* and numerical information in a natural-sampling (nonnormalized subsets) structure, and (3) using both frequency terminology and a natural-sampling structure. The nested sets view predicts equally good performance in the two natural-sampling (subset) conditions, regardless of chances or frequency wording. The ecological rationality view predicts better performance in the natural frequency condition and good performance in the natural sampling of chances condition only when it is interpreted as involving frequency information.

The problem presented in the introduction was the text of the *naturally sampled frequencies* condition, and the numerical information formats in the other conditions were the following:

> [*Normalized Chances*]: There was a 5% chance than an applicant was accepted. If the applicant was accepted, there was a 60% chance that he/she passed the oral test. However, if the applicant was rejected, there was still a 20% chance that he/she passed the oral test. Imagine Jean is an applicant taking the entrance examination. Out of the _____ chance(s) that Jean will pass the oral test, there are _____ chance(s) she will be accepted.
>
> [*Chances with Natural Sampling*]: An applicant had 5 chances out of 100 of being accepted. 3 of the 5 chances of being accepted were associated with passing the oral test. However, 19 of the remaining 95 chances of being rejected were also associated with passing the oral test. Imagine Jean is an applicant taking the entrance examination. Out of the _____ chance(s) that Jean will pass the oral test, there are _____ chance(s) she will be accepted.

In all versions, this task was followed by a forced choice question: "Which of the following best describes how you thought about the information and reached your answer to the above problem? (circle one)":

- I thought about the information as a single application with some possibility of having been successful on the oral test and some possibility of having been accepted. [*probability interpretation*]
- I thought about the information as a large number of applications, some of which were successful on the oral test, and some of which were accepted. [*frequency interpretation*]
- Other: I thought about the information as ____________.

A final item asked the participants whether they had any training or education in conditional probabilities and, if so, to describe that training. None of the affirmative responses to this question indicated significant or unique experience that would affect their performance.

Results

The results are reported in Table 1. The participants' ability to reach the correct answer to this task (3/22) was significantly affected by the type of presentation format [$\chi^2(2) = 12.25$, $p = .002$].[1] Specifically, the normalized percentages format was exceptionally difficult (0% correct); chances given in a nonnormalized natural-sampling

Table 1
Performance of Participants in Experiment 1

Presentation Format	Overall Correct Responses %	Overall Correct Responses Freq.		Interpretation of Numerical Information: Single Event %	Single Event Freq.	Frequency %	Frequency Freq.	Other %	Other Freq.		Conditional Correct Responses: Single Event %	Single Event Freq.	Frequency %	Frequency Freq.
Normalized chances	0.0	0/28	→	60.7	17/28	28.6	8/28	10.7	3/28	→	–	–	–	–
Chances with natural sampling	10.7	3/28	→	64.3	18/28	32.1	9/28	3.6	1/28	→	5.6	1/18	22.2	2/9
Naturally sampled frequencies	32.1	9/28	→	28.6	8/28	60.7	17/28	10.7	3/28	→	37.5	3/8	29.4	5/17

Note—%, normalized percentage; Freq., actual frequency; conditional correct responses = correct responses/interpretations; $n = 28$.

format improved performance to 10.7%; and natural frequencies (no chances wording) yielded the best performance (32.1%). Indeed, the difference between the latter two conditions was nearly statistically significant [$\chi^2(1) = 3.82, p = .051, \phi = .261$], even though the only format change between them was the use/absence of the chances wording.[2]

About 60% of the participants in both chances conditions (normalized chances and chances with natural sampling) indicated that they thought about the data in terms of a single-event probability, whereas about 60% of the participants in the naturally sampled frequencies condition interpreted the data in terms of frequencies. Although the sample size is too small to draw strong conclusions, those participants who reported thinking about the nonnormalized chances as frequencies (i.e., a series of multiple episodes) were four times more likely to obtain the correct answer than were those who reported thinking about the same problem as a single-event probability (22% vs. 6%).[3] Interestingly, the participants in the naturally sampled frequencies condition showed relatively good performance regardless of their interpretation of the numerical information.

EXPERIMENT 2

Experiment 2 was designed to replicate the findings of Experiment 1, but using different phrasing in the forced choice question following the reasoning task. Specifically, the results from Experiment 1 might be criticized as biased because the phrasing "a single application" matched the text of the chances conditions, whereas the phrasing "a large number of applications" matched the natural frequency condition.

Method

Participants. The participants were 61 undergraduates (52 of them female and 9 male) from the same source as that in Experiment 1. Their average age was 27.2 years.

Materials and Procedure. The procedure and format of the materials were the same as those in Experiment 1, utilizing only the chances with natural sampling and the naturally sampled frequencies conditions (in which there were informative levels of correct performance). The follow-up question, however, was revised to minimize any leading content that may have produced a response bias due simply to the surface wording of the judgment task. The participants were asked to select from the following:

- I thought about the information as a large number of applications, each of which is either successful on the oral test or not successful, and each of which is either accepted or is not accepted. [*frequency interpretation*]
- I thought about the information as a large number of applications, each of which has some possibility of having been successful on the oral test and some possibility of being accepted. [*probability interpretation*]
- Other: I thought about the information as __________.

None of the participants who indicated that they had any training or education in conditional probabilities had significant or unique experience that would affect their performance.

Results

The results are reported in Table 2. The participants were significantly more likely to reach the correct answer in the naturally sampled frequencies condition, as compared with the chances with natural sampling condition [53% vs. 7%; $\chi^2(1) = 16.11, p < .001, \phi = .514$]. Of the participants in the chances with natural sampling condition, 68% indicated that the chances frequencies were interpreted as single-event probability, whereas 57% of the participants in the naturally sampled frequencies condition indicated that the natural frequencies were interpreted as frequencies. Once again, although the small sample size limits strong conclusions, the participants who reported a frequency interpretation of the information phrased as *chances* were more than twice as likely to obtain the correct answer than were those who reported thinking about the same problem as a single-event probability (12.5% vs. 4.3%; see note 3). The participants in the naturally sampled frequencies condition again showed similar and relatively good performance regardless of their interpretation of the numerical information.

EXPERIMENT 3

The results of Experiments 1 and 2 indicate that numerical information labeled as *chances* can be interpreted as either a probability or a frequency—including as a natural frequency. Therefore, the finding that chances (presented within natural sampling) can elicit correct Bayesian reasoning apparently bears little direct relevance to the question of whether or not natural frequencies tend to elicit Bayesian reasoning.

An additional assertion in Girotto and Gonzalez (2001) is that performance is strongly influenced by the form of the actual Bayesian inference question at the end of a problem. Their argument is that "questions asking for the separate computation of the two terms of a ratio elicit cor-

Table 2
Performance of Participants in Experiment 2

	Overall Correct Responses			Interpretation of Numerical Information							Conditional Correct Responses			
				Single Event		Frequency		Other			Single Event		Frequency	
Presentation Format	%	Freq.		%	Freq.	%	Freq.	%	Freq.		%	Freq.	%	Freq.
Chances with natural sampling (n = 31)	6.5	2/31	→	67.7	21/31	25.8	8/31	6.5	2/31	→	4.3	1/21	12.5	1/8
Naturally sampled frequencies (n = 30)	53.3	16/30	→	33.3	10/30	56.7	17/30	10.0	3/30	→	50.0	5/10	47.1	8/17

Note—%, normalized percentage; Freq., actual frequency; conditional correct responses = correct responses/interpretations.

rect responses, if the information structure allows reasoners to easily obtain these terms . . . , [whereas] questions which do not force reasoners to consider the two terms of the normalized ratio will not elicit correct responses" (p. 252). For example, the type of questions used in the preceding experiments should elicit better performance because both of the two requested numbers were followed by separate descriptors, as compared with questions that placed the descriptors together and requested a response in "one step" (see, e.g., note 2).

Girotto and Gonzalez's (2001) data support their claim, and to some extent their claim may be true, but the results of Experiments 1 and 2 suggest, alternatively, that question formats that encourage a frequency interpretation should facilitate Bayesian reasoning. By this account, some of the results found in Girotto and Gonzalez (2001) can just as easily be accounted for not by the question's syntactic format, but by the degree to which the question format elicits frequency representation.

Method

Participants. The participants were 120 undergraduates (79 of them female and 41 male) at a large public university in the Midwestern United States. Using participants from a top-tier, national university should improve the levels of performance overall, relative to Experiments 1 and 2 (Brase, Fiddick, & Harries, 2006), thus providing slightly clearer results in the more difficult conditions. All consented to participate in partial satisfaction of a research participation component of their class. Their average age was 18.5 years.

Materials and Procedure. Each participant was given a single sheet with some brief instructions and a Bayesian reasoning problem (the medical diagnosis problem, also used in Girotto & Gonzalez, 2001). All the participants received exactly the same chances Bayesian reasoning problem:

> There is a newly discovered disease, Disease *X*, which is transmitted by a bacterial infection. Here is some information about the current research on Disease *X* and efforts to test for the infection that causes it.
>
> A person has 4 chances out of 100 of having the infection. There is a test to detect whether or not a person has this infection, but it is not perfect. Specifically, 3 of the 4 chances of having the infection were associated with a positive reaction from the test. However, 12 of the remaining 96 chances of not having the infection (that is, being perfectly healthy) were also associated with a positive reaction from the test.

An equal number of participants received each of three question forms at the end of the problem: One version referred only to chances for a single person (as in the previous chance frequencies versions); a second version referred to the reference class of "100 chances" (consistent with the problem text); and a third version referred to "100 people" (a frequentist wording):

- Imagine Michael is tested now. Out of the _____ chance(s) that Michael will have a positive reaction from the test, there are _____ chance(s) he will actually have the infection.
- Imagine Michael is tested now, and has the same total of 100 chances. Out of the _____ chance(s) that Michael will have a positive reaction from the test, there are _____ chance(s) he will actually have the infection.
- Imagine a group of 100 people are taking this test. Out of the _____ person(s) who get a positive reaction from the test, _____ of them will actually have the infection.

After the Bayesian reasoning question, each participant was asked to turn over the page and respond to follow-up questions, as in the previous experiments. None of the participants indicated having any significant or unique education in conditional probabilities that would affect their performance.

Results

The results are reported in Table 3. The participants were significantly more likely to reach the correct answer (3/15) in the *100 people* condition, as compared with either of the two conditions using chances questions [52.5% vs. 15%; $\chi^2(1) = 12.58$, $p < .001$, $\phi = .397$]. A single-event probability interpretation was also more common for the conditions using chances question wordings, whereas a frequency interpretation was most common with the 100 people condition. Nevertheless, there was a consistent pattern, in that the participants who reported a frequency interpretation of chances information consistently performed better—by orders of magnitude—than did those who had a single-event probability interpretation (collapsing across conditions: 41.4% vs. 9.4%; see note 3).

DISCUSSION

A series of experiments consistently showed that people do significantly better at Bayesian reasoning tasks when information is presented as natural frequencies, as compared with any type of chances presentation (contradicting Girotto & Gonzalez, 2001). Furthermore, the advantage of frequencies extends not only to information given as explicit objective frequencies, but also to situations in which participants choose a frequentist representation of chances phrasing (which might technically be considered by some theorists to be single-event

Table 3
Performance of Participants in Experiment 3

	Overall Correct Responses			Interpretation of Numerical Information							Conditional Correct Responses			
				Single Event		Frequency		Other			Single Event		Frequency	
Prompt question	%	Freq.		%	Freq.	%	Freq.	%	Freq.		%	Freq.	%	Freq.
Chances wording	15.0	6/40	→	57.5	23/40	32.5	13/40	10.0	4/40	→	8.7	2/23	30.8	4/13
100 chances wording	15.0	6/40	→	65.0	26/40	30.0	12/40	5.0	2/40	→	7.7	2/26	25.0	3/12
100 people wording	52.5	21/40	→	10.0	4/40	82.5	33/40	7.5	3/40	→	25.0	1/4	51.5	17/33

Note—%, normalized percentage; Freq., actual frequency; conditional correct responses = correct responses/interpretations; $n = 40$.

probabilities). That is, successful Bayesian reasoning depends not on the interpretations and representations that might be made by theorists and experimenters, but rather on the clear representation as natural frequencies by the person actually doing the Bayesian reasoning. Indeed, the only situations in which the participants' choice of a frequency interpretation did not improve performance was when the task phrasing was *already* in clear and explicit frequencies.

A theoretically significant aspect of these results is that the tasks used in these experiments (with the exception of the normalized chances condition in Experiment 1) were isomorphic with regard to computational complexity. Nevertheless, there were very different performances across both frequentist/chance presentations and how the participants represented chances numerical information. Thus, these differences in performance are not due to differences in computational complexity.

An increasingly clear, consistent, and interrelated envelope of conditions appear to promote good performance in making judgments under uncertainty, and these conditions fit those indicated by an ecological rationality approach (Gigerenzer, Todd, & the ABC Research Group, 1999). These conditions include frequencies and particular properties related to how quantitative information is typically encountered in the natural world (i.e., natural sampling). Tasks that fall outside of this envelope of conditions in various respects tend to produce poorer performance.

This claim does not imply that the human mind is incapable of utilizing other information formats, either in other settings or even within a particular setting; that would be an *exclusive*, rather than a privileged, representational format. This type of privileged, nonexclusive situation has been described by Sperber (1994) in terms of a *proper domain* (the content with which a cognitive system was actually designed to work) and a larger *actual domain* (the content with which a cognitive system can be persuaded to work). In the assessment of natural frequencies as a cognitively privileged representational format, there have been some confusions across these proper and actual domains. Some tasks claimed to be within the envelope of the proper domain conditions have, in fact, violated those bounds (e.g., by rote conversion of numbers into frequencies, rather than using natural frequencies). Conversely, other tasks claimed to be outside the envelope of the proper domain conditions (e.g., using chances as purported nonfrequencies) have, in fact, actually been within those bounds.

AUTHOR NOTE

The authors thank Sandra Brase, Ray Nickerson, Ulrich Hoffrage, and several anonymous reviewers for comments and advice regarding this research. Correspondence concerning this article should be addressed to G. L. Brase, Department of Psychology, Kansas State University, 492 Bluemont Hall, Manhattan, KS 66506 (e-mail: gbrase@ksu.edu).

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NOTES

1. In this and the following analyses, Fisher's exact probability values are used because the values for some cells (e.g., correct responses when information is not given as natural frequencies) are very small.

2. A potential concern about these results is that the format of the Bayesian inference question may be too *frequentist* to work well with a single-event probability representation of the task information—hence, inhibiting performance for participants with that interpretation. To assess this issue, the normalized chances and chances with natural sampling conditions were rerun using a more open-ended question (i.e., "What are the chances that Jean will be accepted if she passes the oral test? ____ out of _____"; see Experiment 3 for a discussion of such single-step question formats). Performance did not improve using normalized chances (0 correct responses out of 28, with 57% adopting a probability representation) or chances with natural sampling (1 correct response out of 25, with 36% adopting a probability representation).

3. Statistical comparisons of these results are complicated by the fact that they involve comparing small and unequal subgroups within a single condition (i.e., correct responses given single-event and frequency interpretations of chances phrasing; see Tables 1–3). There is a consistency of advantage, ranging from two-fold to four-fold, for frequency interpretations of information over single-event interpretations of information, when chances phrasing is used. One can collapse across all conditions using nonnormalized chances in Experiments 1–3 (i.e., all conditions other than naturally sampled frequencies) to obtain adequate sample size, and the result is clearly significant [7.6% (7/92) vs. 36.0% (27/75); $\chi^2(1) = 20.54$, $p < .001$, $\phi = .351$].

(Manuscript received November 20, 2006;
revision accepted for publication July 29, 2007.)