Memory model of information transmitted in absolute judgment

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Abstract

Purpose – The purpose of this paper is to examine the popular "information transmitted" interpretation of absolute judgments, and to provide an alternative interpretation if one is needed.

Design/methodology/approach – The psychologists Garner and Hake and their successors used Shannon's Information Theory to quantify information transmitted in absolute judgments of sensory stimuli. Here, information theory is briefly reviewed, followed by a description of the absolute judgment experiment, and its information theory analysis. Empirical channel capacities are scrutinized. A remarkable coincidence, the similarity of maximum information transmitted to human memory capacity, is described. Over 60 representative psychology papers on "information transmitted" are inspected for evidence of memory involvement in absolute judgment. Finally, memory is conceptually integrated into absolute judgment through a novel qualitative model that correctly predicts how judgments change with increase in the number of judged stimuli.

Findings – Garner and Hake gave conflicting accounts of how absolute judgments represent information transmission. Further, "channel capacity" is an illusion caused by sampling bias and wishful thinking; information transmitted actually peaks and then declines, the peak coinciding with memory capacity. Absolute judgments themselves have numerous idiosyncracies that are incompatible with a Shannon general communication system but which clearly imply memory dependence.

Research limitations/implications – Memory capacity limits the correctness of absolute judgments. Memory capacity is already well measured by other means, making redundant the informational analysis of absolute judgments.

Originality/value – This paper presents a long-overdue comprehensive critical review of the established interpretation of absolute judgments in terms of "information transmitted". An inevitable conclusion is reached: that published measurements of information transmitted actually measure memory capacity. A new, qualitative model is offered for the role of memory in absolute judgments. The model is well supported by recently revealed empirical properties of absolute judgments.

Keywords Information theory, Cybernetics, Memory

Paper type Research paper

Introduction – psychology and first-order cybernetics

The year 1948 was auspicious. It heralded two cornerstones of first-order cybernetics, *Cybernetics, or Control and Communication in the Animal and the Machine* (Wiener, 1948, reprinted in 1961), the book that founded the cybernetics movement, and *A Mathematical Theory of Communication* (Shannon, 1948; reprinted in 1974), in which Shannon presented the formulation of information theory that is still used today. Shannon's Information Theory gained immediate acceptance and precipitated

This paper was prepared from a talk ("The misapplication of Shannon's Information Theory to Humans") given at the 2008 Annual Meeting of the Cybernetics Society (UK). The author is especially indebted to Professor Martin Smith and Dr David Dewhurst for allowing his participation. Professor Claire S. Barnes made invaluable suggestions during the proofreading of the text.

Kybernetes
Vol. 40 No. 1/2, 2011
pp. 80-109

0368-492X
DOI 10.1108/03684921111117942

a new journal, *IEE Transactions in Information Theory*, to handle the mass of ensuing research. Shannon's theory also enabled the writing of a particularly influential paper that dealt with social science rather than engineering. That paper, which appeared in *Psychological Review*, was entitled "The amount of information in absolute judgments" (Garner and Hake, 1951). Its authors introduced an information theory analysis of "how accurately the *O* (observer) perceived which of several alternative stimuli occurred on a particular presentation, or how much information the *O* obtained about which stimulus occurred" (Garner and Hake, 1951, p. 459), that is, "the amount of information which the stimuli transmit to an *O*" (Garner and Hake, 1951, p. 459). The Garner and Hake approach was just as quickly accepted in experimental psychology as Shannon's mathematics had been in engineering. Subsequent to Garner and Hake there were hundreds of published estimates of the information transmitted in absolute judgments.

The Garner-Hake approach has greatly affected the study of human perception, and continues to do so today. As the British Historian Alan Collins noted, information "was to be a central term in the development of accounts of cognition" (Collins, 2007, p. 54), and Garner and Hake (1951) were at the forefront of that effort. Papers that use the Garner-Hake approach continue to be published; Garner and Hake (1951) has been cited at least 171 times to date, according to the online Institute for Scientific Information database, and the Garner-Hake measure is taught to psychology students from contemporary textbooks. However, the constituency of those who use the Garner-Hake approach is much broader than might at first appear. The Garner-Hake computations were most highly popularized not by Garner and Hake themselves, but by the first published review of the Garner-Hake method and its results, that of Miller (1956b). Miller's erudite review has been cited at least 4,589 times to date in sources on psychology, general cybernetics, systems theory, information engineering, human factors, management, neurology, and music. The Garner-Hake approach was popularized further by Attneave (1959) in a review monograph, since cited at least 809 times. Attneave's book included a thorough summary of the empirical results of the time, as well as a detailed account of all of the necessary mathematical operations.

The information measure that was introduced by Garner and Hake (1951) and popularized by Miller (1956b) and Attneave (1959) was part of the movement to provide:

> [. . .] an explanatory framework that would dissolve the human-machine boundary and lead to psychological explanations expressed as formal mathematical models that would be, in essence, communication and controls systems dealing with information (Collins, 2007, p. 52).

However, the use of the Garner-Hake method has been paralleled by persistent doubts (starting with Cronbach, 1955) about whether it tells much, if anything, about the physiological processing of information. The present paper supplies justifications for those doubts, simply by examining the Garner-Hake approach. The paper does not rely upon opinions expressed in available review papers, because those reviews have all accepted, without question, the Garner and Hake declaration that their method quantifies transmitted information. Rather, the present paper returns to the basics. The first topic is Shannon's (1974) algebra, which Garner and Hake adopted to process their data. We then review the Garner and Hake method itself. The latter proves inappropriate. Further, there is a reasonable alternative interpretation that has existed all along. That interpretation will be expanded into a new model of what Garner and Hake actually measured.

A very brief review of Shannon's Information Theory

Shannon (1974) quantified the amount of information passing through what he called a "general communication system", a system that Shannon illustrated with a simple box-and-stick model. Figure 1 shows a somewhat more detailed version of the system, made from Shannon's accompanying description. In Shannon's own words, the system comprises:

- "An *information source* which produces a message or sequence of messages to be communicated to the receiving terminal".
- "A *transmitter* which operates on the message in some way to produce a signal suitable for transmission over the channel".
- "The *channel* is merely the medium used to transmit the signal from transmitter to receiver".
- "The *receiver* ordinarily performs the inverse operation of that done by the transmitter, reconstructing the message from the signal" finally.
- "The *destination* is the person (or thing) for whom the message is intended" (all quotations from Shannon, 1974, p. 5).

n "events" are possible, and their respective probabilities of occurrence are known and are denoted p_i, $i = 1, \ldots, n$. When an event happens, it becomes an "outcome". The outcome is uncertain when $n > 1$. Figure 2 shows event and outcome. An outcome is accompanied by reduction of uncertainty, which is a gain in information. Shannon argued that:

- uncertainty is a function of the p_i, and a continuous one;
- when $p_i = 1/n$ (i.e. all events are equiprobable), an increase in n causes an increase in uncertainty; and
- uncertainty is the same regardless of the number of successive steps leading to the outcome.

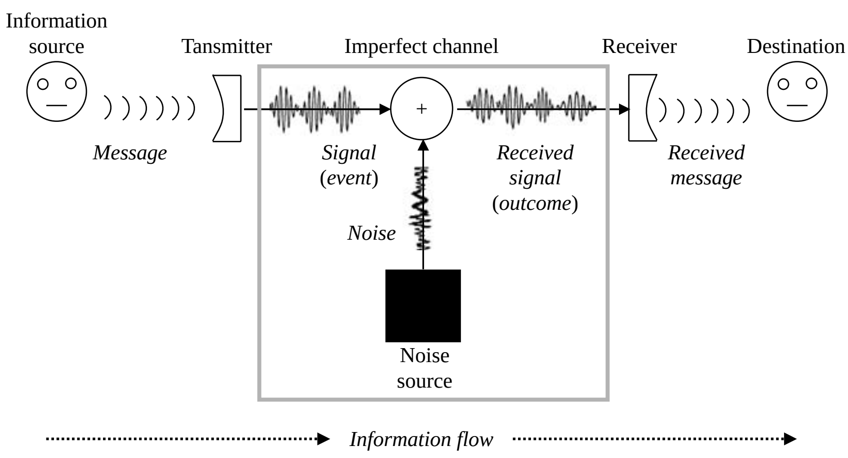


Figure 1. Shannon's general communication system

Source: After Shannon (1974)

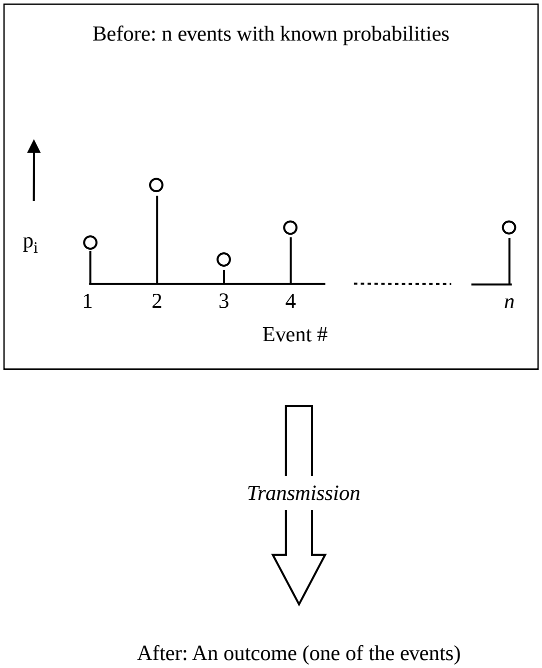


Figure 2.
Events and outcomes according to Shannon (1974)

Shannon proved that the amount of "uncertainty", "choice", or "information" that is inherent to the set of n events is:

$$\textit{The stimulus information } I_S,$$

$$\text{where } I_S = -K\sum_{i=1}^{n} p_i \log p_i, \; K \text{ is constant}, \; K > 0. \tag{1}$$

K "amounts to the choice of a unit of measure" (Shannon, 1974, p. 17), so Shannon set $K = 1$. When all events are equiprobable, I_S is at its maximum, log n. Events can be symbols "k", for which:

$$I_S = -\sum_k p(k) \log p(k). \tag{2}$$

The "confusion matrix"

Information transmitted

Transmission errors occur, so that some symbols are not received as transmitted. The algebra was potentially quite complicated; Shannon (1974) simplified it by assuming that any symbol received is one of the symbols available to send. Denoting $p_j(k)$ as the probability of transmission of symbol k given reception of symbol j, Shannon derived:

$$E_S = -\sum_j \sum_k p_j(k) \log p_j(k), \text{ the stimulus equivocation/uncertainty/entropy}, \tag{3}$$

hence:

$$Information\ \ transmitted\ \ I_t = I_S - E_S$$
$$= -\sum_k p(k)\log p(k) + \sum_j\sum_k p_j(k)\log p_j(k). \qquad (4)$$

Thus, the computation of information transmitted, I_t, requires:

- what symbols were transmitted;
- what symbols were received; and
- the number of times each symbol received corresponded to each symbol transmitted.

The latter values are the elements of the confusion matrix.

The confusion matrix in Shannon's computation of information transmitted

Figure 3 shows the Shannon confusion matrix (after the descriptions in Shannon, 1974). The different columns of the confusion matrix represent the different kinds of symbols sent (events) and the rows of the confusion matrix are labeled by each possible symbol that can be received (outcomes). The matrix entries thus show how many times one particular possible event occurred as one particular possible outcome. When no errors occur, $I_t = I_S$, and the confusion matrix has nonzero entries only on its diagonal; otherwise the transmission lacks fidelity (it has "noisiness").

	Symbol sent (event)						
Symbol received (outcome)	1	2	•	k	•	n	Row totals
1	N_{11}	N_{12}	•	N_{1k}	•	N_{1n}	$N_{1.}$
•							
2	N_{21}	N_{22}	•	N_{2k}	•	N_{2n}	$N_{2.}$
•	•	•	•	•	•	•	
j	N_{j1}	N_{j2}	•	N_{jk}	•	N_{jn}	$N_{j.}$
•	•	•	•	•	•	•	
n	N_{n1}	N_{n2}	•	N_{nk}	•	N_{nn}	$N_{n.}$
Column totals	$N_{.1}$	$N_{.2}$	•	$N_{.k}$	•	$N_{.n}$	$\sum = N$

$$\textit{Total number of symbols received} = \sum_{j=1}^{n} N_{j.} = \sum_{k=1}^{n} N_{.k} = \textit{Total number of symbols sent} = N.$$

Notes: N_{jk} – the number of times that symbol k is actually received as symbol j. $p(j) = N_{j.}/N$ the probability of receiving j; $p(k) = N_{.k}/N$ the probability that k was transmitted; $p_k(j) = N_{jk}/N_{.k}$ the probability of receiving j, having transmitted k; and $p_j(k) = N_{jk}/N_j$ having received j, the probability that k had been transmitted
Source: After Shannon (1974)

Figure 3.
Claude Shannon's confusion matrix

The use of Shannon information in sensory psychology

The conduct of the "category" or "absolute judgment" or "absolute identification" experiment

Shannon's Information Theory has been used to measure human performance in an experiment that has taken on three interchangeable names over the years – "category classification", "absolute identification", or "absolute judgment". The latter expression is the oldest and most popular. As noted earlier, Garner and Hake (1951) introduced Shannon's Information Theory to the analysis of the data. But the experimental method is much older; it was already old when reviewed by Wever and Zener (1928). Absolute judgment presents human subjects with sensory stimuli that are made to vary in one or more physical attributes. Physical intensity is one example of a commonly used attribute, corresponding, for example, to the sensation of loudness (for auditory stimuli) or of brightness (for visual stimuli). When only intensity (for example) is varied, the other physical attributes (e.g. frequency, for a tone, or hue, and for a color or a light) are held constant as best as possible. The varied attribute has a continuum of values, called the "event continuum". The experimenter splits the event continuum into adjacent ranges, the "stimulus categories", with the restriction that each category cannot be smaller than the empirical psychophysical just-noticeable-difference (jnd) in the stimulus attribute. For tone intensity, for example, Garner (1953) used 4, 5, 6, 7, 10, or 20 categories. Categories are named or numbered in rank order according to the magnitude of the varied attribute. Thus, ten categories of tone intensity, say, would be labeled 1-10, or labeled as "very weak" to "very strong" in ten steps. One experimental stimulus was chosen for presentation from each category. As Garner and Hake (1951, p. 452) explained, "we are representing ranges or classes of events with a single stimulus value [for each range]".

A set of response categories are then chosen, which are adjacent ranges of the stimulus attribute continuum, just like the stimulus categories. Each research participant receives sessions of familiarization, in which the stimuli representing the stimulus categories are assigned by the subject to the response categories. This is the act of categorization. Its principle is that:

> The range of stimuli may be placed along a dimension or continuum; furthermore, the responses which *O* [the subject or "observer"] is to learn may be scaled and placed in a consistent relationship or correlation with the stimulus continuum (Gibson, 1953, p. 408).

For initial familiarization and practice, the stimuli are presented first in (typically) ascending order of the magnitude of the attribute that is varied, and then in random order of that magnitude. When practice is over and the subsequent trials are to be counted, the presentation order is always randomized. Garner and Hake (1951) did not prescribe that the number of stimulus and response categories be equal; if they are unequal, however, the stimuli must be forcibly parceled out amongst the response categories by the subject. Not surprisingly, this mismatch affects I_t, the latter generally being largest with equal numbers of stimulus and response categories (Eriksen and Hake, 1955a; Bevan and Avant, 1968; Kintz *et al.*, 1969). Thus, equal numbers became the norm, so that the categorization task became absolute identification, that is, correct naming of the presented stimuli.

The subject continues to practice identifying the stimuli until their performance shows no obvious further improvement. Their performance is used to make a personal equal-discriminability scale of the stimulus attribute (Garner, 1952). Stimuli that are equidistant – those that are the easiest to tell apart, which should give the largest I_t – are then used. Subjects practice the absolute judgment task before each day's data recording. For judged attributes such as auditory tone frequency or intensity, brightness of colors, and concentration of tastants or odorants, equal discriminability meant equal spacing along logarithmic scales. In contrast, equal spacing on linear scales was used for judgments of length or distance, and for judgments involving muscular force (as, for example, for weights held in the hand).

Garner and Hake (1951): connecting information theory to perception

Garner and Hake (1951) computed I_t after the algebra of Shannon (1974; equations (2)-(4) above). What differed was the confusion matrix; in the Garner-Hake confusion matrix, rows represent response categories, and columns represent stimulus categories. Figure 4 shows the matrix. Each matrix entry represents the number of times the stimulus representing a particular stimulus category was judged by the subject as being within a particular response category. Or, in terms of absolute identification, each matrix entry is the number of times that the stimulus of the respective column was named as the stimulus of the respective row. I_t was computed from the matrix elements according to equation (4), usually using base 2 for the logarithms, thus quantifying I_t in "binary units per stimulus". These units are usually abbreviated to "bits/stimulus", and are the units used from here on. An information transmitted of 1 bit/stimulus is equivalent to the perfect identification of two stimuli, 2 bits/stimulus to perfect identification of four stimuli, and so on.

Garner and Hake (1951) justified their use of Shannon's Information Theory through the following model. Garner and Hake (1951, p. 446) declared that "The stimulus can be

	Stimulus category						
Response category	1	2	·	k	·	n	Row totals
1	N_{11}	N_{12}	·	N_{1k}	·	N_{1n}	$N_{1.}$
·							
2	N_{21}	N_{22}	·	N_{2k}	·	N_{2n}	$N_{2.}$
·	·	·	·	·	·	·	·
j	N_{j1}	N_{j2}	·	N_{jk}	·	N_{jn}	$N_{j.}$
·	·	·	·	·	·	·	·
n	N_{n1}	N_{n2}	·	N_{nk}	·	N_{nn}	$N_{n.}$
Column totals	$N_{.1}$	$N_{.2}$	·	$N_{.k}$	·	$N_{.n}$	$\sum = N$

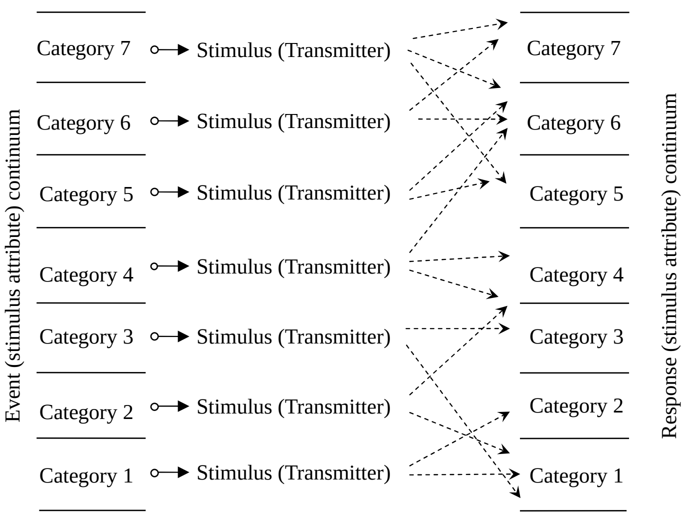
$$\textit{Total number of response} = \sum_{j=1}^{n} N_{j.} = \sum_{k=1}^{n} N_{.k} = \textit{total number of stimuli} = N$$

Notes: N_{jk} – the number of times the subject took a stimulus from category k and placed it into category j · $p(j) = N_{j.}/N$ the probability that the subject placed the stimulus in category j; $p(k) = N_{.k}/N$ the probability that the presented stimulus was from category k; $p_k(j) = N_{jk}/N_{.k}$ the probability that the stimulus was placed in category j when in fact it was from category k; and $p_j(k) = N_{jk}/N_{j.}$ the probability that the stimulus was from category k when in fact it was placed into category j

Figure 4.
How Garner and Hake (1951) use the Shannon confusion matrix

thought of as an event which occurs with a certain probability". Whatever stimulus attribute was manipulated in the absolute judgment experiment formed an "event continuum" containing a potentially enormous number of events. When choosing stimuli for presentation, "we are representing ranges or classes of events with a single stimulus value" (Garner and Hake, 1951, p. 452). The experimental stimuli, to Garner and Hake, were the elements of the Shannon communication system that transmit the event (Figure 1). Thus, I_t computed from the absolute judgment experiment using the Garner-Hake confusion matrix was "the amount of information about the event continuum which a particular range of stimulus values [those used in the experiment] can transmit" (Garner and Hake, 1951, p. 452), or "the amount of information which the stimuli transmit to an *O*" (Garner and Hake, 1951, p. 459). Hartman summarized the Garner-Hake approach, for his auditory stimuli: "We were to regard our [nine] tones as representing nine items of knowledge about a particular continuum" (Hartman, 1954, p. 6). Figure 5 shows Garner and Hake's model of absolute judgment as information transmission.

Generally, in absolute judgment experiments, only one stimulus is presented at a time (Wever and Zener, 1928). According to Garner and Hake, at the moment of its presentation each stimulus becomes the Shannon transmitter. Garner and Hake did not name the other elements of Shannon's general communication system (Figure 1) – that is, the source, the sent message, the channel, the received message, the receiver, and the destination. It seems prudent to know their identities within the Garner-Hake approach, but such must be inferred. The message would seem to be the succession



Notes: Shown for seven stimulus categories and seven equivalent response categories; the stimulus attribute of interest (for example, physical intensity) is a continuum, which is cut into categories; each category is customarily represented by a single stimulus that "transmits information" about the attribute continuum; the stimuli are presented in random order of their position within the continuum; the subject assigns each stimulus to a response category (dashed lines); the latter choice, being subjective, will not always be the correct one; thus, information transmitted I_t can be less than stimulus information I_S

Figure 5. The Garner and Hake (1951) concept of information transmission in absolute judgment experiments

of stimuli given by the experimenter, thus (although the stimuli appear to be the transmitters) the experimenter had to be the source. However, the experimenter also recorded the subject's responses, thus being the receiver of those responses, the responses therefore being the received message. The experimenter also computed the information transmitted, thus becoming the ultimate destination of the received message. Altogether, there was just one role left for the human subject – that of "channel". It was left to Miller (1956a, p. 129) to state that role explicitly and to state its use, as follows: "If a human operator is regarded as a communication channel with stimuli for inputs and responses for outputs, it is possible to estimate maximum rates of transmission through him". That is, the psychologist's confusion matrix yields "the amount of information transmitted (by the human channel) from the set of stimuli to the set of responses" (Landau *et al.*, 1974, p. 239) or, in the words of Kintz *et al.* (1969, p. 241), the "information transmitted through the subject":

Some unsolved problems with the Garner and Hake approach

The average reader will by now have detected some inconsistencies in the Garner-Hake approach. For example, stimuli were treated as "transmitters" but also as things transmitted. Note well that Garner and Hake (1951) provided no mathematical or logic proof that their interpretation of Shannon's (1974) Information Theory actually measured transmitted information in an absolute judgment experiment. And, no proofs appeared later in the "citation classics" of Miller (1956b) and Attneave (1959). Apparently, the Garner-Hake approach was taken on face value by those who used it. The exception was Cronbach (1955), who made important technical criticisms that were largely ignored at the time and that have been rarely mentioned since. (Cronbach's criticisms are not easily summarized in brief, and the reader is referred to Cronbach (1955).)

Recall that the inputs and outputs of Shannon's general communication system (Figure 1) are, respectively, the "events" and the "outcomes". Garner and Hake (1951) computed the amount of information transmitted in perception by treating stimulus categories as events, and response categories as outcomes. When the number of stimulus categories equaled the number of response categories (i.e. the usual laboratory procedure) the stimulus categories became both the events and the outcomes. Each stimulus category, however, was represented empirically by a stimulus. Thus, each entry in the Garner-Hake confusion matrix represents how often which stimulus was identified as which by the experimental subject. That is, stimuli were the *de facto* events and the subject's identifications of them were the *de facto* outcomes. Those outcomes were thus not events, being identifications of stimuli rather than the actual physical stimuli, the Garner-Hake "events". Compare and contrast this to Shannon's general communication system, within which each outcome is one of the events.

It can be shown that not only is the Garner-Hake approach not consistent with Shannon's ideas, it is not even consistent with its own. Garner and Hake (1951, p. 452) admitted that "Which events (or how many) are represented by which particular discrete stimulus is an arbitrary matter", thus maintaining that stimuli represent events. But they also stated that "The stimulus can be thought of as an event which occurs with a certain probability" (Garner and Hake, 1951, p. 446), that is, the stimulus is the event. All told, Garner and Hake described stimuli as transmitters, and as representatives of events, and as actual events. Thus, they assigned any stimulus three different roles, roles that might seem mutually exclusive. Furthering the confusion, Garner and Hake never actually defined "outcomes".

Hopefully, it has become evident to the reader that there are serious problems with the Garner and Hake view of information transmission. And there are more. Recall that Garner and Hake treated the human experimental subject as the communication channel of the absolute judgment experiment. However, Garner and Hake (1951, p. 459) also declared that I_t represents "how accurately the *O* [observer] perceived which of several alternative stimuli occurred on a particular presentation, or how much information the *O* obtained about which stimulus occurred". That is, the subjects themselves obtain the information, by doing the experimenter's job of computing the information transmitted. That makes the subjects the receivers of the message, and perhaps also the message's destination, not just the channel.

In sum, Garner and Hake (1951) applied Shannon's computations of information transmitted to the psychologist's absolute judgment experiment. Close inspection of Garner and Hake (1951) reveals a variety of conflicting accounts of how the absolute judgment experiment represents the object of Shannon's algebra, that is, the transmission of Shannon information within a Shannon general communication system. The Garner-Hake computation of information transmitted appears to be inconsistent with the Shannon computation of information transmitted. As such, what does the Garner-Hake I_t represent?

The theoretical behavior of the human "channel capacity"

Answering the latter question requires a brief foray into the psychophysical interpretation of the capacity of a communication system, as will be shown. Human subjects, as channels, were not assumed to carry a limitless amount of information. In that regard, Miller (1956b) explained something that Garner and Hake (1951) had omitted from their discussion:

> If the human observer is a reasonable kind of communication system, then when we increase the amount of input information [i.e. stimulus information, I_S] the transmitted information will increase at first and will eventually level off at some asymptotic value. This asymptotic value we take to be the channel capacity of the observer (Miller, 1956b, p. 82).

Empirically, when the categories are few and wide, each stimulus should be correctly identified by the subject, such that I_t equals I_S, the information available in the set of stimuli used in the absolute judgment experiment (equation (2)). Now customarily, absolute judgment experiments use a fixed overall stimulus range. Therefore, increasing the number of categories employed decreases the width of each category. This makes the subject sometimes assign stimuli to the wrong categories. I_t may still increase, because the stimulus information I_S has increased with the number of categories; recall that when n stimuli are equiprobable (the usual experimental situation) then $I_S = \log(n)$. As the stimulus range is partitioned into finer and finer categories, however, I_t will hypothetically plateau, because the subject will prove unable to obtain any more information during the absolute judgment task. Indeed, as Miller (1956b, p. 86) noted:

> On the basis of the present evidence it seems safe to say that we posses a finite and rather small capacity for making such unidimensional judgments and that this capacity does not vary a great deal from one simple sensory attribute to another.

This capacity was dubbed "channel capacity". It was especially promoted by Alluisi (1957) and became widely accepted. Figure 6 shows channel capacity.

In the now-famous "The magical number seven, plus or minus two" (Miller, 1956b), Miller declared the channel capacity to be "7 ± 2" categories. Miller's 7 ± 2 categories correspond to 2.81 bits/stimulus minus 0.49 bits/stimulus and plus 0.36 bits/stimulus. MacRae (1970, p. 112) noted Miller's (1956a, b) work, noting that "The quantitative correspondence between quite different sensory modalities with this technique made it seem likely that some fundamental aspect of performance was being measured". Many further attempts to measure channel capacity followed the publication of Miller's paper.

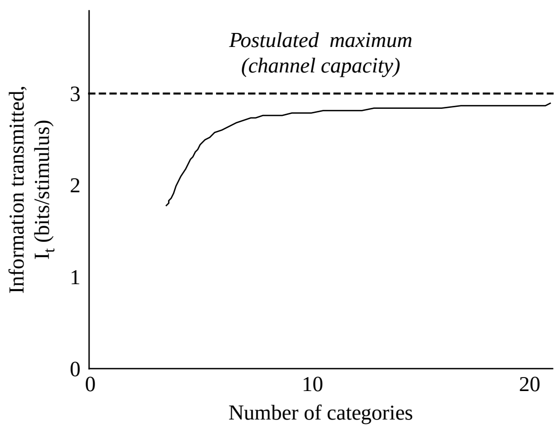
The actual behavior of the human channel capacity

Information transmitted versus number of judged stimuli

Acceptance of a human channel capacity was broad, but early on, Cronbach (1955, p. 15) sounded a subtle warning:

> Pseudo-constancies can arise because of the way measuring procedures are devised, or from balancing of opposing effects. In many studies where some degree of invariance is reported, the experimental design has been insufficiently penetrating.

Miller (1956b) and especially Alluisi (1957) had proselytized the notion of an asymptote in I_t, but actual data sometimes differed. For example, Pollack (1952) obtained I_ts for pitch naming (frequency identification) of tones, using either of 3, 4, 5, 6, 7, or 10 tones. Pollack discovered that I_t was maximal for 7 tones. Pollack subsequently did a similar experiment using either of 3, 4, 5, 6, 7, 8, 10, or 14 tones, and found again that I_t peaked at 7 tones, subsequently declined, and then climbed suddenly again for 14 tones. Chapanis and Halsey (1956) found a peak and subsequent decline for color naming of spots of light; I_t varied from 3.20 bits/stimulus for ten colors to 3.35 for 12 colors to 3.66 for 15 colors to 3.20 for 17 colors. Engen and Pfaffmann (1959) found that I_t for odor intensity for either of 3, 5, 7, 10, or 13 concentrations of amyl acetate (banana odor) peaked for seven concentrations and then fell slowly with increasing concentration.



Note: With increasing numbers of judgment experiment (and hence increasing numbers of different presented stimuli), I_t would hypothetically asymptote at some empirical maximum

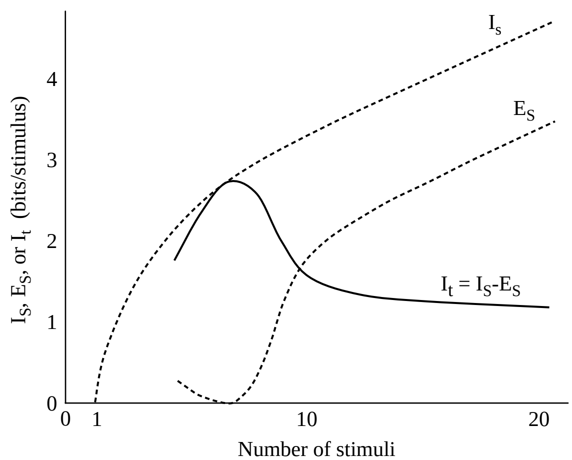
Figure 6.
Hypothetical channel capacity, according to the literature

Beebe-Center *et al.* (1955) found the same sort of rise and fall for the perceived intensity of saltiness; they used either of 3, 5, 9, or 17 saline solutions. Figure 7 shows the empirical rise and fall of I_t.

Despite evidence of an apparent maximum, the empirical behavior of I_t with increase in the number of judged stimuli remained unclear. At times I_t seemed to asymptote, at others to peak and then decline. Garner (1953) provided an inadvertent clue to the mystery. In separate experiments, his subjects were required to identify either of 4, 5, 6, 7, 10, or 20 tones of the same frequency but differing intensity, according to their loudnesses. Where Garner differed from other investigators was in how he processed the judgments. He used two methods. First, he pooled all of the judgments over all of the participants, then computed I_t. Subsequently, he completely re-computed an I_t for the subject group, by calculating I_t individually for each subject, then averaging the I_ts across subjects to get a final, single I_t. For the pooled raw data (i.e. first calculation method), I_t peaked for five stimuli ($I_t = 2.32$ bits/stimulus), then declined to 1.62 bits/stimulus for 20 stimuli. However, the across-subject-average I_t (second calculation method) reached an asymptote, thus being higher for larger numbers of stimuli than the I_t for pooled data. To summarize, the plot of I_t versus number of stimuli differed by computational method. Now, most studies use the second method, because it is easier when the experimenter uses different stimulus sets for each subject, which is often done so that each subject has their own unique scale of equidistant stimuli.

A statistical bias in the calculation of information transmitted

The second of Garner's computations that give a subject group I_t, the popular one, in fact contains a sampling bias. That bias causes I_t to be overestimated, and it increases as the total number of stimulus presentations involved in computing I_t diminishes relative to the number of stimulus categories (minus one, and assuming one stimulus per category),



Notes: The plot of I_t is styled after Beebe-Center *et al*. (1955), Chapanis and Halsey (1956) and Engen and Pfaffmann (1959); the plot of E_S ($= I_S - I_t$) is inferred from the behaviors of I_S and of I_t

Figure 7.
Stimulus information I_S for *n* equiprobable stimuli ($I_S = \log_2(n)$), stimulus equivocation E_S (equation (3)), and information transmitted I_t (equation (4)) as functions (in logarithms to base 2) of the number of stimuli presented in an absolute judgment experiment

multiplied by the number of response categories (minus one). The source of the bias had been recognized by theorists for some time, but it was MacRae (1970) who brought the bias to general attention with a paper in *Psychological Bulletin*. There, MacRae detailed the bias and its implications. Recall that the number of different stimuli used as "events" typically equals the number of stimulus categories, which in turn usually equals the number of response categories. Thus, from above, the overestimation of I_t increases with the number n of different stimuli used, given a fixed total number of stimulus presentations in the experiment trial. Now, I_S depends only on n (equation (2)), not on the number of stimulus presentations, and thus remains fixed and without bias. But as equation (4) shows, I_t also involves the stimulus equivocation E_S (equation (3)), which involves the number of stimuli and the number of presentations (it depends upon the entries in the confusion matrix, Figure 4), and is therefore biased. Knowing all this, the excess in the value of I_t can be estimated under some reasonable statistical assumptions (MacRae, 1970). I_t can be accordingly adjusted. MacRae (1970) did this for many sets of published data, and finally concluded that channel capacity was an artefact. The experiments had failed to involve a sufficient number of stimulus presentations, and thus had been "insufficiently penetrating", just as Cronbach (1955) had warned. Avoiding such bias in the future requires pooling all data across all subjects into a single confusion matrix, before computing I_t, i.e. the first method used by Garner (1953), and the one less convenient for the experimentalist.

Despite MacRae's conclusions, later papers still spoke of channel capacity (Russell, 1981; Fulgosi *et al.*, 1987; Murphy *et al.*, 2006), sometimes called "information processing capacity" (Donkin *et al.*, 2009). Indeed, as Murphy *et al.* (2010, p. 800) declared, "It has long been known that unidimensional sensory channels are limited in terms of the amount of information they can transmit (channel capacity; Miller, 1956a, b)". The reasons for the remarkable persistence of such beliefs were probably those of yore:

> The view that transmission remains constant with increasing stimulus information survived in spite of some contrary evidence because the usual effect of bias was to produce a μ-shaped curve with sufficient irregularity for no trend to be compellingly evident. This allowed experimenters and reviewers to plot a best-fitting horizontal line and identify it as the channel capacity [. . .] When a choice of curves was available to represent an experimental design the most flat-topped has usually been chosen [. . .] (MacRae, 1970, p. 119).

Remarkably, the findings of Garner (1953) and of MacRae (1970) were largely ignored; experimenters continued to use large numbers of stimuli to probe imaginary channel capacities. For example, Marteniuk (1971) employed 16 different stimuli, and so did Russell and Marteniuk (1974; cited by Russell, 1981, and graphed therein). Ward (1991) used 21, and Mori and Ward (1995) used 16, with the respective human subjects being given no more than the usual familiarization training.

An explanation of the peak in the information transmitted

Empirically, subjects commit errors when they identify stimuli. The error rate can be used to understand the peak in I_t with increase in number of stimuli that was actually found by Beebe-Center *et al.* (1955), Chapanis and Halsey (1956) and Engen and Pfaffmann (1959), and which, according to MacRae (1970), should be found in all unbiased computations of I_t. To begin, note that for a constant rate of mistakes, I_t will monotonically increase and eventually asymptote at what would appear to be a "channel capacity". But an asymptotic channel capacity is an artifact of biased computations

(MacRae, 1970). Thus, the probability that a subject will misidentify a stimulus – let that quantity be called the error rate – cannot be constant.

Why would a subject's error rates differ? Quite possibly because absolute judgments "are probably made by comparing the present stimulus with some average subjective standard" (Garner and Hake, 1951, p. 446). That is, "absolute judgments" are not truly absolute; most likely they involve comparisons. If so, we must then ask what "events" are being compared to what "outcomes". Sensations are evoked by stimuli whose intensities exceed the absolute detection threshold. The sensations rise monotonically with stimulus intensity. Therefore, stimulus and response categories, the columns and rows, respectively, of the Garner-Hake confusion matrix (Figure 4), represent ranges of sensations, as far as the human subject is concerned. An absolute judgment consists, therefore, of identifying a sensation. That sensation may be compared to internal standards, perhaps even without conscious awareness of the comparison process. The internal standards must be the mental remnants of the sensations evoked by previous stimuli, in particular, the exemplar stimuli that were given during the training and practice phases of the experiment. The process of comparison is repeated over and over to yield the entries of the confusion matrix. Comparison will become more challenging with increasing number of stimuli to be identified. For example, for four stimulus/response categories, categorization should be easy, although the subject will occasionally misidentify a stimulus. But categorization becomes harder when the number of categories increases to seven. Nonetheless, I_S has risen as the number of categories has risen, so that I_t for seven categories will exceed that for four. For 12 categories, however, the memory traces of the exemplars are not as distinct as for seven categories, so that the increase in I_S caused by the greater number of stimuli is offset by a greater error rate, hence an increase in E_S, and consequently a decline in I_t. As the number of different stimuli employed increases, then intuitively, the error rate must also increase; the subject has too much to deal with attentionally, as will be explored below. This notion is not well elaborated in the literature. Some critical number of stimuli will be reached at which the increase in stimulus information is outstripped by the increase in error rate. I_t will therefore rise, peak, and subsequently decline. I_S and E_S tradeoff to produce the rise and fall of I_t that is seen for unbiased computations. Figure 7 shows that tradeoff.

The role of memory in absolute judgments

An interesting coincidence

Miller (1956b) briefly reviewed the contemporary memory literature and noted that we can correctly remember 7 ∀ 2 items. Much evidence for that capacity had appeared over 1887-1925 (Guilford and Dallenbach, 1925) and appeared subsequent to Miller (1956b) over 1956-1973 (Broadbent, 1975). However, the literature since Broadbent, reviewed by Cowan (2000), suggests a memory capacity of only 4 ∀ 1 items. That is, 7 ∀ 2 is really just the sum of memory stores of 4 ∀ 1 and 3 ∀ 1. In that case, memory capacity correlates to I_t: typically, $I_t = 2$ bits/stimulus, representing correct identification of four stimuli, for minimally trained subjects (Eriksen and Hake, 1955a; Hawkes and Warm, 1960; Tulving and Lindsay, 1967; Vianello and Evans, 1968; Bechinger *et al.*, 1969; Landau *et al.*, 1974; Locke, 1974, 1975; Fulgosi *et al.*, 1987; Mori and Ward, 1992, 1995; Hettinger *et al.*, 1999). I_t can exceed 2 bits/stimulus when subjects receive more practice, i.e. when they are allowed further learning, improving their memory of the stimuli (Pollack, 1953; Ward, 1953;

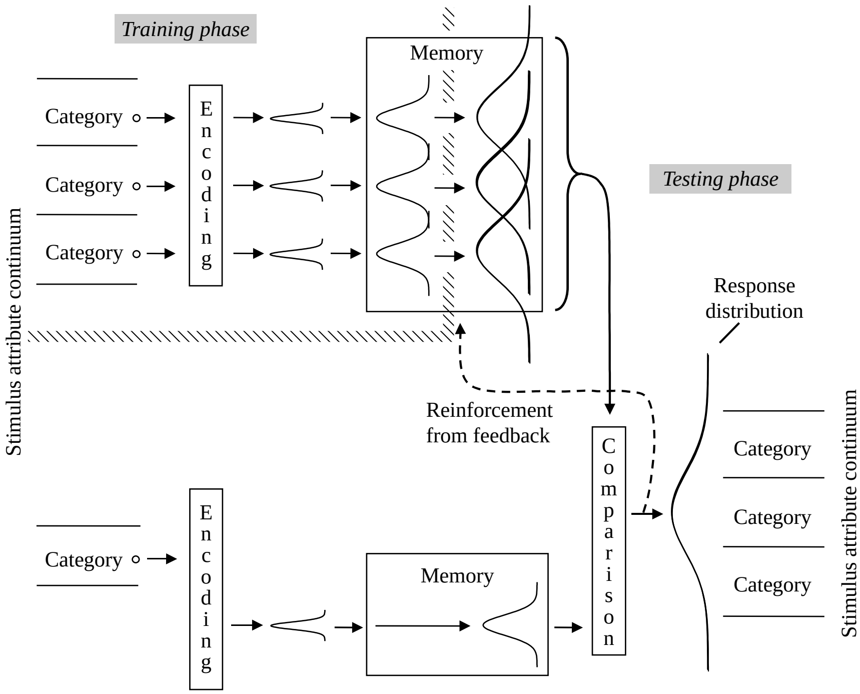
Hanes and Rhoades, 1959; Pylyshyn and Agnew, 1962; Terman, 1965; Feallock *et al.*, 1966; Friedman, 1967; Steedman, 1967; Cuddy, 1968; Egeth and Pachella, 1969; Fulgosi and Bartolovic, 1971; Heller and Auerbach, 1972; Fulgosi and Zaja, 1975; Fulgosi *et al.*, 1984, 1986).

What relation of memory capacity to information content?

The apparent equality of memory capacity and maximum I_t for lightly trained subjects can be interpreted in two ways: either information capacity represents a constant amount of memory, or memory capacity represents a constant amount of information. If the latter, then the memory span should change, being small when individual items in memory contain much information, and vice versa. Empirically, such is not the case for memory of strings of unrelated words or digits, as reviewed by Miller (1956a), a conclusion thoroughly confirmed (Slak, 1974). We must therefore now examine the converse, that is, whether maximum I_t for lightly trained subjects is independent of memory capacity. For this, there are no authoritative sources in the literature. The present author therefore reviewed roughly 60 empirical papers on I_t.

Absolute judgments appear to be sensitive to residual memories of previous stimuli (Wever and Zener, 1928; Campbell *et al.*, 1958; Miller and Engen, 1960; Di Lollo, 1964). The absolute judgment task can be altered to patently reduce or remove the memory load, and in such cases information transmission rises remarkably (Klemmer and Frick, 1953, replicated by Petiot and Parrot, 1980; Chapanis and Overbey, 1971). Tulving and Lindsay (1967) took a different tack; they found that when subjects were presented with two difference kinds of stimuli simultaneously (e.g. lights and tones), judging one right after the other reduced the respective I_ts relative to those found when judging just one kind of stimulus. Tulving and Lindsay concluded that distraction (a central neurological effect) was to blame for the decrease, rather than information capacity, the latter presumably being determined at the sensory receptor. Egeth and Pachella (1969) reported similar findings for sugar/salt solutions judged on both saltiness and sweetness.

Absolute judgments involve idiosyncracies that might not be anticipated when viewing the human being as a Shannon communication system. One such idiosyncracy is that I_t improves when the subject is continuously informed of the correctness of their judgments, called "feedback" (Hartman, 1954; Engen and Pfaffmann, 1959; Agnew *et al.*, 1966; Friedman, 1967; Steedman, 1967; Ward and Lockhead, 1970; Siegel, 1972; McNicol, 1975; Mori and Ward, 1995). The Shannon general communication system has no such active process (although Shannon did eventually illustrate and discuss such a process (Shannon, 1974, Figure 8). Thus, feedback in absolute judgments violates the model system that underlies Shannon's algebra. Another idiosyncracy of absolute judgments is that repeating them, with the subject given appropriate breaks, always improves I_t (Pollack, 1953; Ward, 1953; Eriksen and Hake, 1955a; Hanes and Rhoades, 1959; Hawkes, 1961; Pylyshyn and Agnew, 1962; Terman, 1965; Feallock *et al.*, 1966; Friedman, 1967; Steedman, 1967; Cuddy, 1968; Vianello and Evans, 1968; Egeth and Pachella, 1969; Fulgosi and Bartolovic, 1971; Fullard *et al.*, 1972; Heller and Auerbach, 1972; Fulgosi and Zaja, 1975; Costall *et al.*, 1981; Fulgosi *et al.*, 1984, 1986; Hettinger *et al.*, 1999; Petrov and Anderson, 2005). In terms of Figure 7, this practice effect makes the peak in I_t move to the right. Terminating practice allows forgetting, and judgment scores then typically decline, as reviewed by Gibson (1953). Practice consolidates a task in memory;



Notes: See text; the response distributions are assumed, for simplicity's sake, to be symmetric; in fact, however, they will become increasingly skewed towards the nearest end of the stimulus range as the respective stimulus gets closer to that end; this happens because the subject can make mistakes towards lower or higher stimuli when the stimulus is in the middle, but as the stimulus nears the ends, subjects will increasingly make mistakes in one direction, i.e. towards the center, because that direction offers the greater number of different erroneous choices; skewness is greatest at the very ends of the stimulus scale, because there the subject can only err towards the middle (see succeeding figures)

Figure 8.
A new, memory-centered model of absolute judgments

in contrast, Shannon's general communication system has no accommodation for either learning or forgetting.

There is yet another interesting idiosyncracy of absolute judgments: that I_t increases when subjects are better motivated (Rouder *et al.*, 2004). This factor is not accommodated by the Shannon general communication system. Still another factor not accommodated by Shannon is that I_t improves with increase in the physical range covered by a given number of different test stimuli (Eriksen and Hake, 1955a; Pollack, 1956; Engen and Pfaffmann, 1959; Hawkes, 1961; Garner *et al.*, 1966; Mori and Ward, 1992; Brown *et al.*, 2005). However, as stimuli get farther apart physically, they become more distinct, hence easier to remember. As such, up to some point I_t should remain constant as the number of stimuli decreases but their physical separation increases, a notion confirmed by Alluisi (1957).

I_t decreases under "contrast", in which each stimulus to be judged is preceded by a fixed stimulus that is physically outside the range of the judged stimuli (Heintz, 1950, replicated by Salzinger, 1957). Compare this to the Shannon general communication system, in which inserting a fixed symbol between each message symbol sent, and then assembling the message only from the message symbols, should not affect the information transmitted. However, "contrast" can be explained if the fixed stimulus is used as an unhelpful reference standard in memory for identifying the stimuli. Consider now absolute judgments without a fixed contrast stimulus. There is nonetheless a tendency:

> [. . .] for a response to a given stimulus category to be higher when the preceding stimulus is higher than the one being judged, and lower when the preceding stimulus is lower (Garner, 1953, p. 377; see Tresselt's review, 1947).

This type of sequential dependence is called "assimilation". Assimilation is robust, because it happens even under feedback (Holland and Lockhead, 1968), which should have counteracted any judgment bias. Some experiments have found both assimilation and contrast (Sherif *et al.*, 1958, replicated by Parducci and Marshall, 1962; McKenna, 1984), and assimilation is found even when contrast is not used (Rouder *et al.*, 2004; Brown *et al.*, 2005; Petrov and Anderson, 2005). Note that information transmission in the Shannon general communication system has no equivalent to assimilation. However, Luce *et al.* (1982) performed elaborate experiments which suggested that a stimulus is a memory aid for the next stimulus when the two are similar and is a distractor when the two differ. A supporting limiting case is that when the two stimuli are the same, the later of the pair is more likely to be correctly identified than otherwise (Costall *et al.*, 1981).

Absolute judgments are also subject to a phenomenon called "masking", that is known outside of the literature on absolute judgments. In masking, one stimulus interferes with a psychological aspect of another. The masker stimulus and the masked stimulus need not coincide ("simultaneous" masking); the masker may precede ("forward masking") or even follow ("backward masking") the masked stimulus. In absolute judgments, masking empirically causes I_t to fall; backward masking (Ward, 1991) and simultaneous, forward, and backward masking (Mori and Ward, 1992) have been found. Current wisdom is that backward masking occurs physiologically centrally and involves memory (see the comments in Nizami *et al.* (2002)). We may consider forward or backward masking in absolute judgments to be a form of "contrast", for which the I_t from the Shannon general communication system should not have changed, but did, perhaps because the sensation evoked by the masker was stored in memory and used as a reference for the stimulus identification.

Another unique aspect of absolute judgments is "end-anchoring". There, the greatest and least stimuli of the stimulus set are identified with greater accuracy than the stimuli in-between (Pollack, 1952, 1953; Garner, 1953; Eriksen and Hake, 1955a; Engen and Pfaffmann, 1959; Pylyshyn and Agnew, 1962; Terman, 1965; Spitz, 1967; Steedman, 1967; Cuddy, 1968; Holland and Lockhead, 1968; Snelbecker and Fullard, 1972; Lacouture, 1997; Lacouture and Lacerte, 1997; Elvevag *et al.*, 2004; Rouder *et al.*, 2004; Brown *et al.*, 2005; Petrov and Anderson, 2005; McCormack *et al.*, 2002; Murphy *et al.*, 2010). Eriksen and Hake (1955a) confirmed, through several elaborate experiments, that the greatest and least stimuli are used as judgment standards. Indeed, end-anchoring decreases when the use of end stimuli as standards is prevented or obstructed (Pollack, 1953; Cuddy, 1968; Heller and Auerbach, 1972; Locke, 1975) and disappears altogether when a stimulus set (such as a "color wheel") has no apparent ends (Volkmann and Engen, 1961; Costall *et al.*, 1981). Also, when the middle stimulus of an odd-numbered stimulus set is made distinct from its neighbors by greater spacing, it can be named correctly with the same frequency as for the end stimuli (Neath *et al.*, 2006; see also Lacouture, 1997). Presumably, greater perceptual distinctness aided remembrance and hence identification (Neath *et al.*, 2006).

Siegel (1972) performed what was arguably the single most important experiment on absolute judgments. Siegel hypothesized that when subjects are given feedback stimulus-by-stimulus, the correct answer is remembered, rendering the stimulus easier to identify on its subsequent presentation, the effect presumably declining with increase in the number of stimuli intervening between any two identical stimuli. Siegel confirmed his hypothesis, concluding that "If there is a channel capacity for absolute judgments of unidimensional stimuli, it is an asymptote on forgetting" (Siegel, 1972, p. 125). Aiken *et al.* (1973) confirmed Siegel's results.

And there is more. In principle, stimuli can physically change in more than one dimension, in which case the subject can be asked to separately categorize each dimension. For example, a tone's intensity and its frequency can both be varied, and the subject asked to identify the intensity and then the frequency (or vice versa). I_t for overall identification by intensity and frequency is then computed using special multidimension versions of equation (2)-(4) (Attneave, 1959), although I_t can still be computed separately for each physical dimension. The single-dimension I_ts thus computed are:

- smaller than are found when only one dimension is varied; and
- sum to less than the overall multidimension I_t (Pollack, 1953; Pollack and Ficks, 1954; Beebe-Center *et al.*, 1955; Eriksen and Hake, 1955b; Garner and Creelman, 1964; Lockhead, 1966; Egeth and Pachella, 1969; Fulgosi *et al.*, 1975).

There is no explanation for these observations within the Shannon general communication system. There is, however, a memory explanation: a stimulus possessing multiple unique features is more likely to be correctly identified because, like a human face, it is unique.

On a final note, memory strength seems to be generally independent of stimulus duration, so that if I_t is memory dependent, then it too should be duration independent. That characteristic has been confirmed (Garner and Creelman, 1964; Garner *et al.*, 1966; Egeth and Pachella, 1969; Ward, 1991).

Altogether, a review of a great deal of literature suggests that the absolute judgment task shows behaviors not attributable to a Shannon general communication system. The review also suggests that the maximum I_t found for lightly trained subjects is not independent of memory capacity. In total, then, absolute judgments represent not information transmission, but a test of memory, such that channel capacity is actually memory capacity. The Shannon general communication system is now clearly an incorrect model of the absolute judgment task. A new model in terms of memory will be offered, as follows.

A memory model of absolute judgments

Variability in comparisons

It is well established that as a given stimulus is repeated, a distribution of spike counts results (for hearing, see for example, Nizami and Schneider, 1997; Nizami, 2005). Here, for simplicity, that distribution is assumed to be Gaussian and of equal variance for all stimuli. (The sensory literature generally supports such an assumption, although the appropriate stimulus-intensity scale may be logarithmic rather than linear in intensity, just like the scales used in absolute judgments.) As far as spike counts become sensations, the multiple presentations of any given stimulus, the exemplar for its stimulus category, will thus result in a distribution of sensations. Each sensation presumably becomes a memory trace; thus the traces are distributed. Each memory trace can presumably be accessed when needed, with an efficacy that is assumed to not change over time. What does presumably change over time is the variance of the memory trace, which broadens (memory "decay"). Now, when the subject makes an absolute judgment, the test stimulus evokes a sensation, which instantly becomes a memory that is presumably compared to the memory traces of the sensations evoked by the exemplars. In the experiment, the comparison process for each stimulus covers, on average, the same range of decay of the traces of the exemplars. This is because experimentally, both in the training sessions and in the testing sessions:

- the presentation of the stimuli is randomized in order of the varied physical characteristic(s); and
- the different stimuli are each presented the same number of times.

Because the things to be compared are presumably distributed as Gaussians, the subjects' stimulus categorizations/identifications are also presumably distributed as Gaussians. The response distributions are assumed to be equal in variance. However, at the ends of the stimulus range, subjects can err only towards the center of the range. Thus, it is assumed that when stimuli are near the ends of the stimulus range, the resulting response distributions will become asymmetric, their peaks rising and shifting towards those ends (skewness). The closer the stimulus to the end, then the greater the skewness of the distribution. For all stimuli, the most likely response, represented by the peak of the response distribution, will presumably fall within the correct stimulus category/identity.

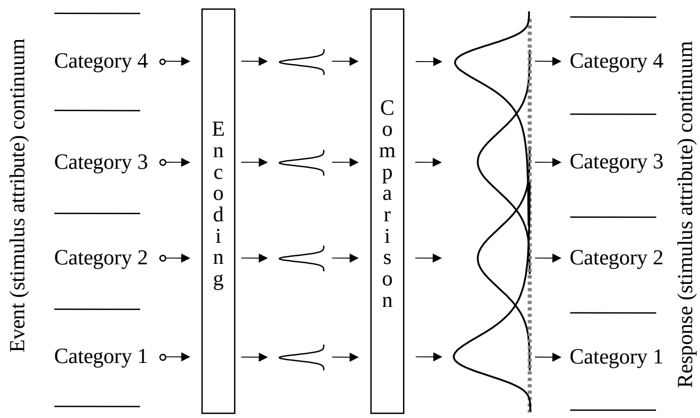
Figure 8 shows the memory model of the categorization/identification process in absolute judgments. In this and subsequent figures, the open dots represent the exemplars, taken from the perceptual center of each category. The upper left quadrant of the illustration, behind the hashed line, shows the training phase. There, the subject is exposed to the exemplars. Here, for the sake of convenience, just three categories are shown. The response categories, to which the stimuli are assigned by the subject, have been omitted from the "training phase" picture for the sake of clarity. In the testing phase (the rest of the picture), a given test stimulus (one of the exemplars) is encoded as it was in the training phase. The resulting sensation evokes a memory trace that is distributed, although not as widely as for the original exemplars because the trace is fresher. The trace is then compared to the traces of some or all of the original exemplars in a categorization decision. Because the traces of the original exemplars are distributed, so are the subject's categorization responses. Note well that Garner and Hake (1951) and their adherents ignored these issues, thus implying that the subjects have perfect memory. The probability that the subject names a particular stimulus as being in a given category is equal to the area, lying between the category's boundaries, under the stimulus' evoked response distribution. Also, recall from above that when correctness feedback is given, categorization/identification gets better, and the relevant memory traces momentarily decrease in variance; hence the path labeled "Reinforcement from feedback".

Anticipated behavior of information transmitted with narrowing of categories

The usual experimental condition for absolute judgments is to keep the overall stimulus range fixed, so that increasing the number of categories, when desired, is done by equally narrowing each category. As categories thus narrow, the number of different stimuli (at one per category) increases. So, too, does the number of memory traces to which the memory of the test stimulus' sensation is compared during the absolute judgment. With stimuli fitted into a fixed physical range, memory traces are crammed into a fixed mental range. Thus, as the number of stimuli increases, the memory of each becomes less distinct; this manifests in the model as an increase of the variance of the distribution of each memory trace. Figures 9-11, respectively, show this behavior as the number of categories increases from four to seven to 12 and the mental impressions of the category boundaries become correspondingly less distinct. The concepts of training, and the conversion of neuronal responses into memory traces, are omitted from the illustration, for the sake of clarity.

Actual distributions of absolute judgments

Surprisingly, little published data could be found on the distribution of subject's absolute judgments, but what exists does support the model. van Krevelen (1951) found symmetrical, single-peaked response distributions of roughly equal variance for tones of 415.30 Hz (in music, G sharp), 440 Hz (A), and 466.16 Hz (A sharp). Those tones were not near the ends of van Krevelen's employed stimulus range (hence their lack of skewness). The judgments were done by persons having an exceptional ability to name tones, called "perfect pitch" (for an explanation and review, see Takeuchi and Hulse, 1993). However, subjects not having perfect pitch (Terman, 1965) produced similar response distributions, for tones of 155.6, 261.6, and 440.0 Hz which (again) were not near the end of the stimulus range. However, the distributions were noticeably wider at 440 Hz than van Krevelen's (1951), and generally widened with increase in frequency.



Notes: See text; categorization mistakes are few; that is, very little cumulative probability (i.e. area under the stimulus-evoked response distribution curve) lies outside the response category for which the distribution is maximum; the subject has still less cumulative probability of misassigning the end stimuli, because the respective response distributions are skewed towards the ends

Figure 9. The distributions of the subject's responses when there are four categories

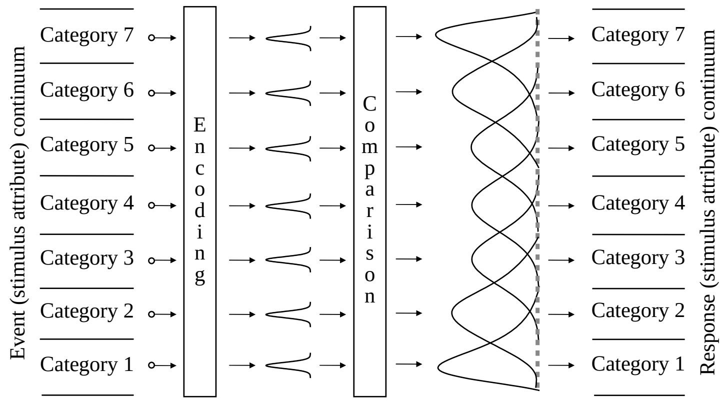


Figure 10.
Similar to Figure 9, but for seven categories rather than four

Notes: The subject makes more misassignments, represented by the wider distributions of their response distributions for all stimuli; nevertheless, as the stimuli approach the ends of the range, the resulting response distributions are more skewed, representing greater probability of correctly identification

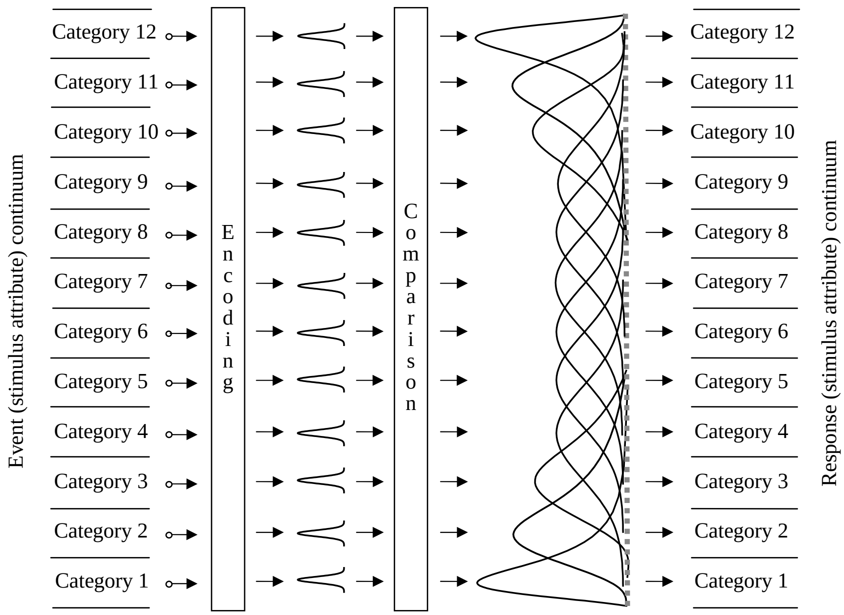


Figure 11.
Similar to Figures 9 and 10, but for 12 categories rather than four or seven

Notes: The subject makes the greatest number yet of misassignments; all response distributions are the widest yet

(In the present model, perfect pitch is an improved memory for tone identity, manifested as the narrowing of distributions of the memory traces of the exemplars, and hence of the distributions of the absolute judgments.) In a different approach, Miyazaki (1988) had subjects differentiate either 180 sawtooth waves representing notes, or 180 synthesized piano notes. Miyazaki found the same distribution phenomena as discovered by van Krevelen (1951) and by Terman (1965), except that distribution variances hardly changed according to stimulus, although distributions did become increasingly skewed as the stimuli neared the ends of the stimulus range. Note that the distributions of the responses can be assembled from the entries in the confusion matrix itself; unfortunately, few papers displayed empirical confusion matrices.

After the first draft of the present manuscript was written (in 2008), the author became aware of some crucial empirical data, as follows. Skewness of response distributions shows clearly for absolute judgments of the duration (McCormack *et al.*, 2002; Murphy *et al.*, 2010) and of the pitch (McCormack *et al.*, 2002) of pure (i.e. single frequency) tones. For 500-Hz tones of various durations, McCormack *et al.* (2002) plotted the proportion of subjects' responses as a function of those responses (e.g. "Tone duration was category 3", etc.), plots that they called "response gradients". These plots, one for each stimulus category k, consist of discrete data points, each representing $p_k (j) = N_{jk}/N_{.k}$ – the probability that the stimulus was placed in category j when in fact it was from category k (for explanation, see Figure 4). The plots of actual $p_k (j)$ are the discrete real-world versions of the theoretical continuous distributions shown in Figures 9-11. That is, the theoretical distributions for seven categories, seen in Figure 10, have their real-world counterpart in the plots of actual $p_k (j)$ for six categories and for nine categories shown by McCormack *et al.* (2002). McCormack *et al.* found similar behavior for what they called the "distribution gradients", the separate plots, for each response category j, of $p_j (k) = N_{jk}/N_{j.}$ (= the probability that the stimulus was from category k when in fact it was placed into category j; see Figure 4). McCormack *et al.* also plotted response gradients of $p_k (j)$ for absolute judgments of pitch (nine different auditory frequencies) and found the same pattern as for tone duration. Later, Murphy *et al.* (2010) confirmed, for durations of 6 tones of 2 kHz, the shapes of the response gradients for duration judgments of 6 tones of 500 Hz found by McCormack *et al.* (2002). Figure 12 shows response gradients of the kind found by McCormack *et al.* (2002) and by Murphy *et al.* (2010).

Overall, then, the predicted response distributions of Figures 9-11 are confirmed for tone duration and pitch. Similar patterns of response gradients were found for rod length (Neath *et al.*, 2006) and for tone duration and for line length (Elvevag *et al.*, 2004). All of these patterns emerge for stimuli that are equally spaced on whatever scale (linear or logarithmic) allows equal discriminability between neighboring stimuli. However, absolute judgments have also been done in which one or more stimuli in the middle of the stimulus set have been separated from the others. In such cases, those "isolated" stimuli should stand out in memory, perhaps to the point that they can be used as anchors for the absolute judgments. In such cases, we would expect fewer identification errors for the isolated stimuli, and in fact that is what occurs (Lacouture, 1997, for lengths of lines; Neath *et al.*, 2006, for tone durations, rod lengths, heaviness of weights, and numerosity of squares). We would expect $p_k (j)$ to correspondingly increase for the isolated stimuli, and Neath *et al.* (2006) illustrate this, at least, for rod lengths (graphs were not provided for the other types of stimuli used). There is yet another effect that is not covered in the simplified model underlying Figures 9-11, namely, that the plot of the empirical response gradients can show greater skewness of $p_k (j)$ for the lowest-magnitude stimulus among the stimuli presented than for the highest-magnitude stimulus. This effect is clearly evident for judgments of tone durations and of line lengths in Elvevag *et al.* (2004). Its origin is still debated.

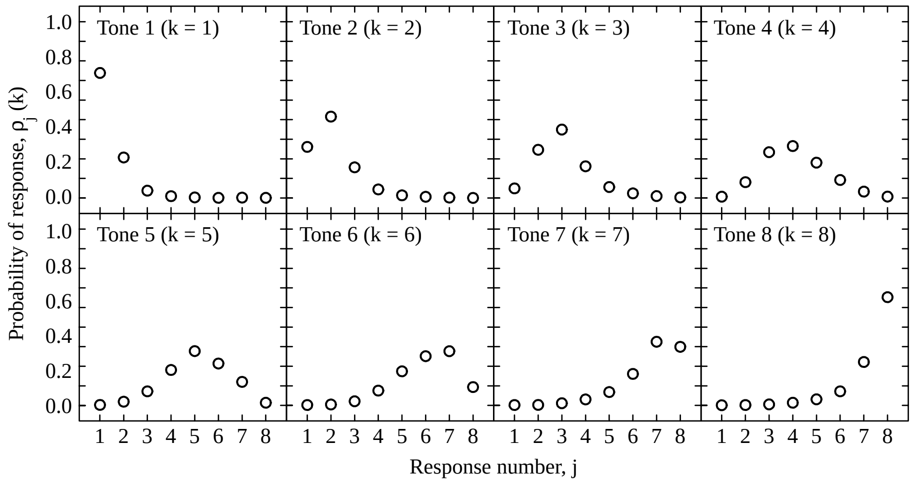


Figure 12.
Actual results of absolute judgments of the duration of a 2-kHz tone

Notes: Tones 1-8 had respective durations of 220, 300, 410, 560, 750, 1,000, 1,310, and 1,700 ms; data points are arithmetic averages of the two sets of data points shown in the upper panels of Figure 5 of Murphy *et al.* (2010), which in turn represented arithmetic averages of scores, respectively, obtained from two groups of experimental subjects (original data kindly supplied by Prof. Dana Murphy); note the wave-like appearance of the plots, imitating the theoretical distributions of Figures 9-11 but suggesting that those distributions should perhaps be more sharply peaked

What is the true limit of "information transmitted"?

Empirical I_ts are always less than their possible maxima, the stimulus information I_S. Explanations were offered in the literature, explanations typified by that of Fulgosi *et al.* (1986, p. 380): "In the process of transforming physical energy into physiological energy and judgments, a significant amount of information is lost". That is, information transmission is noisy. Notwithstanding this engineering "lossy channel" interpretation, we have seen that there is a credible second explanation: that is, that the empirical I_t represents the limits of memory, not those of a noisy transmission channel. As noted above, I_t typically equals or exceeds 2 bits/stimulus, the latter representing four perfectly identifiable categories. But the number four also characterizes modern estimates of memory capacity (Cowan, 2000, 2010), and channel capacity does indeed appear to be memory capacity. Such a result is too neat, of course; as noted above, subjects given extensive practice can produce I_ts that are much bigger than 2 bits/stimulus. Suddenly, memory capacity no longer equals channel capacity. But consider what is achieved during practice: practice consolidates a task in memory. Logically, higher I_ts actually reflect improved memory. This begs the question of how memory capacity can remain constant but memory itself can improve. The answer was found by Ericsson *et al.* (1980) in an unusually painstaking experiment. There, a single experimental subject (Faloon) increased his memory for random digits from seven to 80 digits over 20 months of training. The subject's enhanced ability evidently derived from dividing the presented digits into seven supergroups, each consisting of three groups of three or four digits per group, plus a final group of five digits. Nonetheless, his immediate memory capacity was not believed to have ever been greater than 4 ± 1 digits. The grouping of digits was attributed to "long-term" memory. We may hence postulate that whenever I_t exceeds 2 bits/stimulus, there has been an improvement in the memory used for the task despite a fixed memory capacity. Improvement in empirical I_t with practice is represented by a rightward shift in the peak of the curve for I_t in Figure 7.

Summary

In 1948, Claude Shannon produced his now-famous model of the general communication system (reprinted in Shannon, 1974), and his accompanying equations for computing the amount of information transmitted within that system. Barely three years later, Shannon's work was re-interpreted by the Harvard psychologists Garner and Hake (1951) to suit absolute judgments done in the psychology laboratory. The Garner-Hake reformulation of information transmitted was part of a trend whose impact was profound:

> Born of papers by Claude Shannon and the book, *Cybernetics*, by Norbert Wiener, information theory looked then like the young man in a very great hurry who jumped on his horse and rode off in all directions. Standard-bearers of information theory were plunging into genetics, neurophysiology, sociology, experimental psychology, linguistics, and philosophy with great enthusiasm and greater hopes. Many problems that had long resisted even adequate formulation seemed about to succumb to information theory (Cohen, 1966, p. 1).

The Garner-Hake approach remains in use. It works as follows. A stimulus (visual, auditory, gustatory, olfactory, or somesthetic) is varied in one or more characteristics by the experimenter, and the resulting set of stimuli are assigned to categories according to the varied characteristic(s), again by the experimenter. The experimental subject then learns to identify the stimuli by their categories. Once learned, all of the stimuli are presented again to the subject, singly and randomized by the varied characteristic, and the subject must identify each stimulus by its category. Each stimulus category becomes the column of a Shannon confusion matrix, and each response category becomes a row. Each entry in the matrix thus represents the proportion of times that a stimulus from one particular category is assigned to another particular category. Those proportions lead through Shannon's equations to the information transmitted, I_t. I_t allegedly empirically asymptotes at a limit called the "channel capacity" as the stimulus set gets larger. That is, the psychology literature states that there is a limit to the number of different stimuli that a human being can consistently identify correctly.

The present author examined the behavior of I_t by critically reviewing decades of absolute judgment literature. The alleged asymptote in I_t proves to be an artifact. Further, the Garner-Hake use of information theory has been inconsistent. Also, absolute judgments are characterized by idiosyncracies such as effects of feedback, practice, motivation, stimulus range, contrast, assimilation, masking, end-anchoring, and so on and so forth. Those idiosyncracies cannot be explained in terms of a Shannon general communication system. Indeed, I_t cannot be said to have a known upper limit. I_t can be improved by intensive training, such that the number of consistently correctly identified stimuli can greatly exceed the apparent limit of four, or at best seven, that was posited in the Garner-Hake literature. Such an improvement can be understood if absolute judgment is regarded as a test of memory. In memory experiments, it has been well established that only four to seven stimuli can be consistently correctly identified without special training. But these are the same numbers that arise from absolute judgments (again, without special training). Because of these concerns, the present paper offers a novel model of absolute judgment. In that model, training using stimulus exemplars establishes memory traces of the sensations evoked by the stimuli. Stimuli subsequently presented for judgment create traces that are compared to the memories of the exemplars. Over many such comparisons, a distribution of absolute judgments results, which widens with increase in the number of different stimuli judged. The model mandates that judgment distributions for the stimuli at the extremes of the employed stimulus range are skewed and that the skewness increases with increase in the number of different stimuli judged. The latter are found in the literature.

Conclusions

Shannon's (1948; reprinted in 1974) Information Theory has been employed since 1951 to quantify the human ability to make absolute judgments (Garner and Hake, 1951). That analysis treated humans as "communication channels" of limited capacity. However, the literature contains substantial evidence that the alleged "channel capacity" is in fact a memory capacity, a capacity whose value is well established from memory experiments. Thus, absolute judgment experiments can be envisioned as tests of memory, and a model for such has been presented here. In retrospect, further use of absolute judgments to assess "channel capacity" are redundant, and even retrogressive because of their diversion of time and effort away from better interpretations of human capability.

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