Research Article

ABSOLUTE IDENTIFICATION WITH SIMPLE AND COMPLEX STIMULI

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Abstract—*It is well known that people can perfectly identify only a handful of distinct unidimensional stimuli, such as line lengths, but can identify thousands of complex stimuli, such as letters and words. This result is consistent with capacity limits in identifying unidimensional stimuli but not complex stimuli. The experiments reported here tested this theoretical dissociation using Luce's (1963) Similarity Choice Model to measure the psychological distance between stimuli in line-length-identification and letter-identification tasks. The psychological distance between line-length stimuli decreased with the number of to-be-identified stimuli; this result is concordant with capacity limits in unidimensional absolute identification. Surprisingly, the opposite result held in letter identification. Psychological distance between letters increased with an increased number of to-be-identified stimuli. This result indicates an opposite type of processing deficit: People process letters more efficiently with more choices.*

One of the best explored findings in human perception and cognition is the inability of people to perfectly identify more than seven or so unidimensional stimuli in an absolute identification task (see Miller, 1956, for a review). In an absolute identification task, a participant is presented with one stimulus chosen randomly from a fixed set of stimuli. Each stimulus in the set is paired with a unique response. In the unidimensional absolute identification task, the stimuli vary on a unidimensional continuum, such as brightness, length, or auditory frequency. One seminal example of the inability of people to perfectly identify more than seven unidimensional stimuli comes from Pollack (1952), who presented listeners with eight tones that varied in frequency. He found that although each tone was perfectly discriminable from any other, listeners were only 81% accurate in the absolute identification task. Performance dropped off to 62% when listeners were presented with 14 perfectly discriminable tones. Psychologists have examined absolute identification with unidimensional stimuli in several domains (loudness, brightness, length, stimulus duration) and have found that as more unidimensional stimuli must be identified, performance declines, and does so rapidly. In some sense, this result is not surprising; we expect increasing error rates with increasing numbers of choices. The fundamental question is whether participants' underlying perceptual sensitivity to the stimuli varies with the number of alternatives.

The experiments reported here explored this question about perceptual sensitivity using Luce's (1963) Similarity Choice Model (SCM) to analyze absolute identification data from line-length-identification and letter-identification tasks. SCM provides a measure of the psychological distance between pairs of stimuli. Pairs of stimuli that are separated by a relatively small distance are easily confused, whereas pairs that are relatively far apart are not easily confused. One result presented here is that in line-length identification, as the number of alternatives is increased, the distance between pairs of stimuli decreases. This result is fully concordant with the common belief that there are attentional or mnemonic capacity limits in processing unidimensional stimuli. The general idea is that if processing is limited, participants will not be as sensitive to the stimuli (e.g., they will not be able to perceive fine distinctions among similar stimuli), and hence they will represent stimuli as being close together in a psychological space. Quite surprisingly, the opposite result was obtained with the letter-identification task. The psychological distance between pairs of stimuli increased with increasing numbers of stimuli. That is, sensitivity to letters was better when the participants had a larger set of letters to identify! This finding is novel and counter to the general theme in information processing that processing is affected by mnemonic or attentional limitations that are more salient with increasing numbers of stimuli.

For the purposes of studying perception, SCM forms a natural means of comparing performance on tasks with different numbers of available response alternatives. In SCM, the probability of response *i* to stimulus *j* is given by

$$P_{r_i,s_j} = \frac{\eta_{s_i,s_j}\beta_{r_i}}{\Sigma_k \eta_{s_k,s_j}\beta_{r_k}}. \quad (1)$$

In Equation 1, η_{s_i,s_j} is the perceived similarity of stimulus *i* to stimulus *j*, and β_{r_i} is an internal response bias toward response *i*. Response biases describe the tendencies toward particular responses when the participant is unsure of the target's identity. There are two restrictions on η that allow the model to be identifiable and interpretable. First, the similarity is symmetric (i.e., $\eta_{s_i,s_j} = \eta_{s_j,s_i}$). Second, the similarity of any item to itself is set to 1.

Consider a two-choice task in which on each trial the participant is presented stimulus a or b (and makes response A or B). When the choice rule, Equation 1, is applied, it is possible to estimate η_{s_a,s_b} as well as β_{r_A}. The η_{s_a,s_b} parameter (similarity) is inversely related to the concept of sensitivity and distance: Better identification performance is obtained when the similarities between different stimuli are low. It is common to interpret the quantity $-\log\eta_{s_a,s_b}$ as the psychological distance between stimuli a and b (see, Luce, 1963, p. 114). In this example, the distance between a and b is estimated in a two-choice task. But SCM can be applied to tasks with more than two choices and still yields an estimate of distances for each pair of stimuli. For example, consider a six-choice task in which the participant is presented stimuli a, b, c, d, e, and f, and makes responses A, B, C, D, E, and F. It is possible with SCM to derive an estimate of the distance between s_a and s_b. The question of interest is whether the distance obtained in the two-choice task is different from the distance in the six-choice task. If distances decrease with increasing numbers of alternatives, then the decrease in performance reflects changes in processing that are consistent with the idea of capacity limitations.

Before proceeding, it is reasonable to ask whether SCM is a good model for measuring psychological distance. Indeed, it is. First, and

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most important, not only is SCM testable, but it has been tested repeatedly across a wide variety of domains, including letter identification. Townsend and his colleagues (Townsend, 1971a, 1971b; Townsend & Ashby, 1982; Townsend & Landon, 1982; see also Lupker, 1979) have tested SCM against many competitors and found that SCM consistently performs at least as well as and often better than any competitor. Second, elements of the choice-rule family of models have been incorporated into influential information processing models. Examples include the exemplar categorization models (Nosofsky, 1986; Nosofsky & Palmeri, 1997) and neural network models (Anderson, 1991; Krushke, 1992; McClelland & Rumelhart, 1981; Rouder, Ratcliff, & McKoon, 2000). SCM has even been incorporated into a substantive, template-matching model of letter recognition (Loomis, 1990).

EXPERIMENT 1

SCM was applied to a unidimensional task in which observers identified line segments of different lengths. In the two-choice condition, participants had to identify which one of two line lengths was presented. In the six-choice condition, participants had to identify which one of six line lengths was presented. The two line lengths in the two-choice condition were the two most intermediate line lengths in the six-choice condition. For each participant, the psychological distance between the two intermediary lines was estimated.

Method

Subjects

Six students from the University of Missouri served as participants and received $9.00.

Stimuli

The stimuli were horizontal lines drawn on a computer display. The display was 640 × 480 square pixels. The six line lengths used varied from 60 pixels (2.5 cm) to 110 pixels (4.7 cm) in increments of 10 pixels (0.44 cm). Participants were seated approximately 40 cm from the display.

Design

The number of stimuli presented (and available responses) served as the main independent factor. In one condition, the two intermediate line lengths served as stimuli (lengths of 80 pixels and 90 pixels). In the other condition, all six line lengths served as stimuli.

Procedure

Each trial began with an 800-ms foreperiod in which the display was blank. After the foreperiod, a line was presented. The position of the line on the display varied slightly from trial to trial. The center of the line was the center of the display plus a small (±6 pixels) perturbation sampled from a two-dimensional uniform. The line was presented for 333 ms, and then the display went blank until the participant responded. Participants responded by depressing one of the numbered keys on the top row of a computer keyboard. The 60-pixel line was paired with the "1" key, the 70-pixel line was paired with the "2" key, and so on. After participants responded, the number corresponding to the correct response was displayed for 1 s. The blank screen after feedback demarcated the end of the current trial and the start of the next.

Participants first performed 300 trials of the two-choice condition. Then they performed 700 trials of the six-choice condition. The first 100 trials of each condition were considered practice and not analyzed.

Results[1]

In Figure 1, the psychological distance[2] between line lengths of 80 and 90 pixels in the six-choice condition is plotted as a function of the distance in the two-choice condition. The points numbered 1 through 6 are for the 6 participants in the line-length task. As can be seen, the numbered points are all below the diagonal, indicating that the psychological distance between the two lines was greater in the two-choice condition than in the six-choice condition for every participant.[3] The lettered points are the results from a letter-identification task (Experiment 2), which is discussed next.

EXPERIMENT 2

In this experiment, SCM was applied to a letter-identification task. So that differential error rates in letter identification could be studied, the letters were degraded. They were presented with both forward and backward masks that consisted of an array of symbol characters. Accuracy, which was far below perfect levels, served as the main dependent variable. In the two-choice condition, participants identified the letters *W* and *E*, whereas in the six-choice condition, participants identified *Q*, *W*, *E*, *R*, *T*, and *Y*.

Method

The method for Experiment 2 was similar to that of Experiment 1 with the following differences. Fifteen students served as participants in exchange for credit toward a course requirement. The stimuli were the letters presented in the standard IBM-PC, DOS text font. The number of letters presented (and available responses) served as the main independent factor.

Each trial began with an 800-ms foreperiod in which the display was blank. After the foreperiod, a premask consisting of four "#" characters surrounding a central "$" character was presented for 100 ms. Then, a letter was presented for 67 ms, and it was subsequently masked by a display consisting of four "$" characters surrounding a central "#." This poststimulus mask was displayed for 100 ms. The display was then blank until the participant responded. Participants responded by depressing the "Q," "W," "E," "R," "T," and "Y" keys on a computer keyboard. After participants responded, the correct letter was displayed for 1 s. A blank screen after feedback demarcated the

1. The frequency matrices from Experiments 1 and 2 may be obtained from the author.

2. Model parameters were estimated by minimizing the chi-square fit statistic with the SIMPLEX algorithm (Nelder & Mead, 1965). An acceptable model fit, $\chi^2(10) \leq 18.307$, $p > .05$, was obtained for all 6 participants.

3. Performance tended to increase with practice in both conditions, and there was no evidence of any fatigue effects. Overall, the practice effect strengthens the conclusion that the distance was greater in the two-choice condition than in the six-choice condition because practice effects would have differentially benefited performance in the six-choice condition.

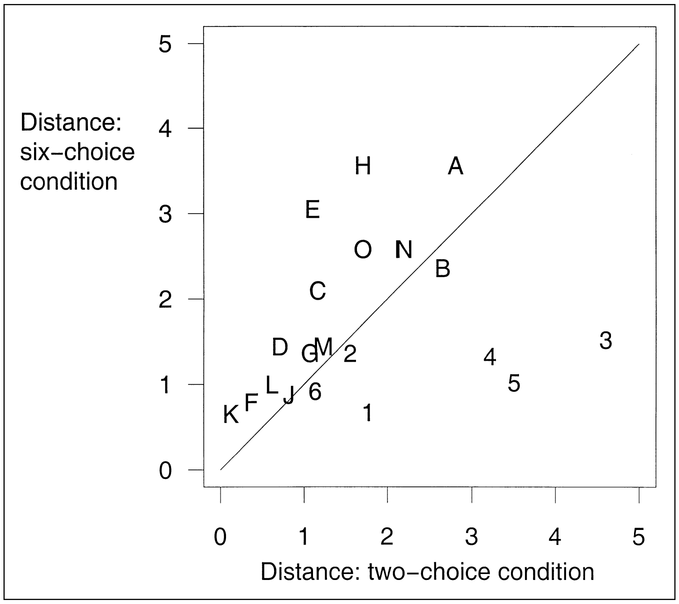

Fig. 1. Estimates of psychological distance in the two- and six-choice conditions of Experiment 1 (line lengths) and Experiment 2 (letters). Each numbered point comes from a single participant who performed line-length identification; it denotes the distance between the two most interior line lengths in the six-choice condition as a function of the distance in the two-choice condition. Each lettered point comes from a single participant who performed letter identification; it denotes the distance between the letters *W* and *E* in the six-choice condition as a function of the distance in the two-choice condition. The diagonal line denotes where the data points would lie if psychological distance was the same in the two- and six-choice conditions.

end of the current trial and the start of the next trial. Every 50 trials, the condition (two-choice vs. six-choice) alternated. The conditions the participants started with were balanced. During the first 100 trials, the stimulus was displayed for an additional 33 ms, to make the task obvious. These trials were discarded in the analysis. Overall, there were 16 blocks of 50 trials each in the experiment.

Results and Discussion

The psychological distance between *W* and *E* was estimated separately in the two- and six-choice conditions and plotted in Figure 1. The estimates of similarity between *E* and *W*, as well as the goodness of fit for SCM in the six-choice condition, are reported in Table 1. The model fit acceptably well, $\chi^2(10) \leq 18.307$, $p > .05$, for all 15 participants. In Figure 1, the points labeled A through O are for the 15 participants in this experiment. Fourteen of the 15 lettered points are above the diagonal, indicating larger distances between stimuli in the six-choice condition than in the two-choice condition.

The results from the line-length task indicate that the distance between the two intermediate lines was smaller in the six-choice condition than in the two-choice condition. This result is consistent with the widely held belief that there are capacity limitations in human information processing of unidimensional stimuli. But, surprisingly, an opposite result was observed for letter identification. The distance between *W* and *E* was smaller in the two-choice condition than in the six-choice condition. One explanation of this finding is that participants were unable to appropriately condition perception on the available choices. Certain features of the stimuli are more informative in the two-choice condition than in the six-choice condition, yet this information appears not to have been used. For example, the perception of the negatively sloped lines of a presented *W* would differentiate it from an *E* and lead to a correct solution in the two-choice case. But this same feature was also shared by the *Y* in the six-choice case, and its perception would not immediately lead to a correct solution. However, it appears that participants were unable to fully use these differentially informative features in the two-choice condition.

Many theories of reading posit that people use context to put logical constraints on the possible identification of letters (McClelland & Rumelhart, 1981). For example, skilled readers already know that the last letter of a three-letter word starting with “ca” will be only one of a few choices (i.e., “r,” “t,” “n,” “p”). If the two-choice condition of Experiment 2 is considered equivalent to the reader having strong contextual information, then the results suggest that readers do not use these constraints in an optimal manner.

ALTERNATIVE MODELS

The finding that psychological distance increases with increasing numbers of choices is surprising and counterintuitive. However, the result was derived within the context of SCM. Should SCM be grossly wrong, the result may not be valid. One sign that the model fits the data well is the acceptable values of the chi-square goodness-of-fit statistic, but the goodness-of-fit statistic alone does not safeguard that the result is valid. R.M. Nosofsky (personal communication, August 22, 2000), in his insightful review of a previous version of this report, suggested that the result may be due to the following mixture artifact: In paradigms in which stimuli are masked, the possibility exists that participants may miss entirely the stimulus presentation on some proportion of the trials. Because the stimuli are not encoded on these trials, the similarity of the stimuli does not affect the response. Responses on these trials reflect a simple guessing process. On the trials in which the stimulus is encoded, performance is governed by SCM; errors reflect confusing the stimulus with similar stimuli. Overall, performance is a mixture between a simple guessing process and SCM. If SCM is used to estimate psychological distance and the data are from such a mixture, the SCM estimates of distance will be too small. But the amount of error in distance estimates decreases with the number of alternatives. If the data are generated from such a mixture in which the psychological distance does not vary with the number of alternatives and the distance is subsequently estimated with SMC, the estimated distance is numerically greater in the six-choice condition than in the two-choice condition. This pattern is the one observed in Experiment 2. Therefore, additional analyses are needed to determine if the greater distances found for the six-choice condition are due to a true perceptual effect or are an artifact from a mixture of error states.

Two mixture models were fit to the data in order to answer this question. The first mixture model (denoted MM_1) comes from Nosofsky (1991, Equation 23). MM_1 posits that participants observing masked stimuli either encode a stimulus or miss it entirely. When stimuli are encoded, errors are due to confusions of similar stimuli, and the response proportions are described by SCM. When stimuli are missed entirely, the participant produces responses with equal probability. The model can be expressed as

Table 1. *Similarities (η) between stimuli and model fits for Experiment 2*

	Model							
	SCM			MM_1				MM_2
Participant	2-choice η	6-choice η	Fit	2-choice η	6-choice η	D	Fit	Fit
A	.056	.033	5.37	.056	.033	1.0	5.37	11.16
B	.073	.081	17.19	.073	.081	1.0	17.19	27.59
C	.307	.137	8.85	.307	.137	1.0	8.85	35.94
D	.493	.264	9.32	.423	.217	.84	7.14	35.29
E	.330	.037	8.09	.330	.037	1.0	8.09	15.30
F	.690	.467	7.17	.594	.405	.77	6.807	10.16
G	.339	.261	9.43	.320	.247	.96	9.38	16.02
H	.182	.019	5.72	.182	.019	1.0	5.723	15.36
I	.123	.080	8.74	.123	.080	1.0	8.74	13.990
J	.436	.434	12.41	.436	.434	1.0	12.41	25.10
K	.884	.584	7.24	.772	.273	.50	6.11	7.95
L	.537	.403	7.46	.511	.368	.93	6.47	13.71
M	.290	.244	15.85	.089	.068	.69	12.81	23.19
N	.104	.071	9.08	.104	.071	1.0	9.08	7.92
O	.183	.082	10.06	.158	.060	.95	9.15	15.19

Note. All fit statistics are chi-square goodness of fit for the six-choice conditions. SCM = Similarity Choice Model (Equation 1); MM_1 = Mixture Model 1 (Equation 2); MM_2 = Mixture Model 2 (Equation 3).

$$P_{r_i,s_j} = \frac{D\eta_{s_i,s_j}\beta_{r_i}}{\Sigma_k \eta_{s_k,s_j}\beta_{r_k}} + \frac{1-D}{N}, \quad (2)$$

where D is the probability that the participant encodes the stimulus.

MM_1 is a proper generalization of SCM (SCM results if $D = 1$) and has an added degree of freedom. Therefore, the chi-square fit statistics must be no larger with MM_1 than with SCM. Although MM_1 is easily applied to the data in the six-choice condition, it is overparameterized for the two-choice condition. But in MM_1, it is assumed that probability of encoding (D) does not reflect the number of choices. The model was first fit to the six-choice condition to obtain an estimate of D, and this estimate was then used in fitting the data from the two-choice condition. With D fixed by the six-choice condition, the model is identifiable for the two-choice condition. Table 1 shows the goodness of fit and parameter values for MM_1. For 8 of the 15 participants, the estimated D was 1.0. Hence, the goodness of fit and the remaining estimates are identical to the values obtained in the SCM analysis for these participants. For the remaining 7 participants, the value of D varied from .50 to .96. As shown in Table 1, the estimated similarity between *W* and *E* was greater in the two-choice condition than in the six-choice condition for 14 of the 15 participants (participant B is the exception).

In MM_1, there is no response bias if participants fail to encode the stimulus (responses occur with equal probability). If there is any degree of response bias, it must be accounted for in the stimulus-encoded state. Model MM_2 was constructed to allow for the opposite scenario, in which there was response bias when the stimulus was not encoded but no response bias when the stimulus was encoded. MM_2 is given by

$$P_{r_i,s_j} = \frac{D\eta_{s_i,s_j}}{\Sigma_k \eta_{s_k,s_j}} + (1-D)g_i, \quad (3)$$

where g_i represents the guessing bias for the *i*th response, $\Sigma_i g_i = 1$. Although MM_2 has one more parameter than SCM, it is not a proper generalization of SDCM (i.e., there are no parameter restrictions on MM_2 that yield SCM). Like MM_1, MM_2 is overparameterized for the two-choice condition. But, as before, the problem can be overcome by estimating D in the six-choice condition and using that estimate in the two-choice condition. The chi-square goodness-of-fit statistic for MM_2 in the six-choice condition is shown in Table 1. Although the model fits acceptably well for 10 of the 15 participants, the fits are numerically larger than the MM_1 or SCM fits for all but 1 participant (participant N is the exception). Therefore, MM_1 and SCM are preferred to MM_2. Overall, there is no evidence to suggest that the main finding (distances between letters increase with increasing number of alternatives) is due to a mixture artifact.

ANALYSIS OF TOWNSEND AND LANDON

The letter-identification result presented here comes from the comparison of only the letters *W* and *E* across conditions. The previously published letter-recognition data of Townsend and Landon (1982) were reanalyzed to show that this result holds for other letter pairs. In Townsend and Landon's experiment, 4 participants identified masked presentations of letters *A*, *E*, *F*, *H*, and *X* over 16 days. The number of letters presented varied from three to five, but within each day, the letters presented were fixed. The psychological distances obtained by analyzing data from the three-choice and five-choice conditions are plotted in Figure 2. Each plot is for a different participant, and each point is labeled by the letter pair it represents. As can be seen, 21 of the 24 points are above the diagonal, indicating a processing inconsistency with poorer performance in the three-condition case relative to the five-choice condition. Although Townsend and Landon did not publish their parameter estimates, they noted that similarities were greater in the three-choice case than in the five-choice case.

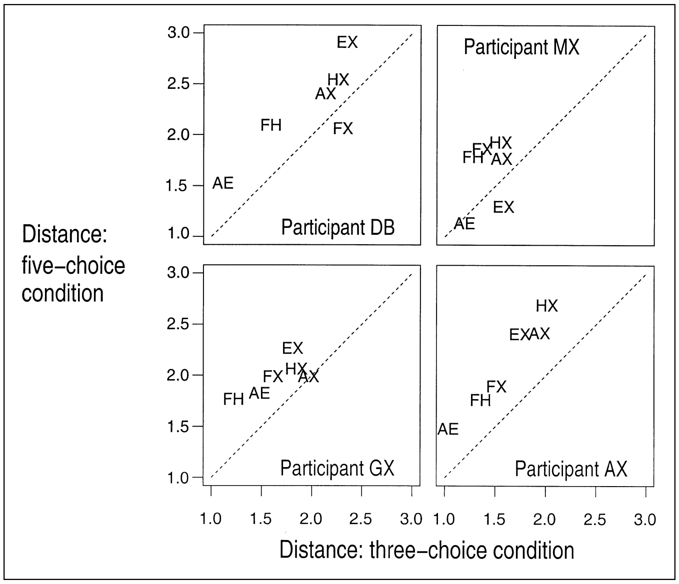

Fig. 2. Estimates of psychological distance from Townsend and Landon's (1982) letter-confusion data. Results for the 4 participants are shown in separate graphs. Each point represents the distance between two letters in the five-choice condition as a function of the distance between the same two letters in the three-choice condition. The diagonal line denotes where the data points would lie if psychological distance was the same in the three- and five-choice conditions.

CONCLUSIONS

SCM analysis yielded processing inconsistencies in letter identification such that performance was hindered as the number of choices was decreased. This finding stands in opposition to that for the absolute identification of line lengths. Participants' performance in identifying line lengths was hindered as the number of choices was increased. Although the latter finding is not new or surprising, the former one is. The conjunction of the findings indicates that there are substantial differences in the processes used in letter and line-length identification.

Many established cognitive theories (Ashby & Townsend, 1986; Edelman, 1995; Landauer & Dumais, 1997) posit that people represent complex stimuli such as letters, words, or objects in a multidimensional psychological space. For example, in Landauer and Dumais's latent semantic analysis theory, words are represented in a space of several hundred abstract dimensions. This multidimensional representation is useful in explaining the fact that people can perfectly identify only a handful of simple stimuli, such as line lengths and tones, but are able to identify hundreds and thousands of complex stimuli, such as objects and words. Because complex stimuli differ on a great number of dimensions, the psychological distances between even nearby stimuli are large. In contrast, simple stimuli differ on one or a few dimensions. Hence, the distance between nearby stimuli is small, leading to confusion. In fact, this type of explanation has been explicitly offered and backed up with a series of intriguing experimental results by Lockhead and his colleagues (Gravetter & Lockhead, 1973; Lockhead, 1970; Monahan & Lockhead, 1977). Although these types of theories are useful in explaining how the number of perfectly identified stimuli changes for simple and complex stimuli, these theories do not account for the experimental results reported here. There is no explanation of how or why the psychological distance between any two letters should increase with increasing numbers of stimuli. The present finding with letter identification is not yet well explained and provides a meaningful constraint on current and future theories of letter recognition.

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