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CROSS-MODALITY MATCHING IN MEMORY PSYCHOPHYSICS: BRIGHTNESS AND LOUDNESS[1]

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Summary.—Performance of subjects in tasks involving estimation of remembered magnitude and cross-modality matching of remembered magnitude for brightness and loudness stimuli was examined in two experiments. Subjects first learned nonsense syllable names associated with exemplars of five levels of brightness and exemplars of five levels of loudness. The stimuli were then removed and one of the nonsense syllable names was given by the experimenter. The subject formed an image of what the stimulus denoted by that name looked or sounded like and gave a judgment of remembered magnitude of that stimulus based upon the intensity portrayed in the image. In Exp. 1 subjects also completed a cross-modality matching task in which a stimulus in one dimension was shown, and subjects then estimated the magnitude that a stimulus in the other dimension would have to possess to match the intensity of the perceived stimulus. Performance was compared with that of a perceptual control group. In Exp. 2 subjects also completed a cross-modality matching task in which they were given the nonsense syllable name of a stimulus from one dimension, formed a vivid image of what the stimulus denoted by that name looked or sounded like, formed an image of a stimulus from the other dimension that possessed the same portrayed intensity as the named stimulus from the first dimension, and then estimated the intensity of the second (unnamed) stimulus. The power function offers an appropriate description of the responses on both the remembered magnitude and the cross-modality matching tasks. Implications for theories of imagery and psychophysics are discussed.

What is the relationship between physical intensity and remembered magnitude? Such a question has been asked with increasing frequency over recent years (e.g., readings in Algom, 1992b; Hubbard, 1992; Kemp, 1988; Kerst & Howard, 1978; Laming & Scheiwiller, 1985; Moyer, Bradley, Sorenson, Whiting, & Mansfield, 1978). One relatively popular way of approaching this issue, suggested by Shepard and Podgorny (1978), is to borrow tools and techniques which were originally developed for the study of perception. The most useful of these tools have come from psychophysics, and the adaptation of those tools to the study of mental representation of remembered magnitudes has been referred to as *memory psychophysics*.

S. S. Stevens (1957, 1975) has described the general form of the relationship between physical intensity and perceived magnitude. This law is of the following form:

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$$P = \lambda S^{\gamma} \qquad [1]$$

where P is the perceived magnitude, S is the stimulus intensity, and λ is a multiplicative constant reflecting the particular units of measurement. The parameter of primary interest is γ, the exponent of the function, which reflects the over-all shape of the relationship between perceived magnitude and physical intensity. Björkman, Lundberg, and Tärnblom (1960) suggested that the same sorts of relationships might be found between remembered magnitude and physical intensity as S. S. Stevens had found between perceived magnitude and physical intensity:

$$M = \phi S^{\eta} \qquad [2]$$

where M is the remembered intensity, S is the stimulus intensity, and ϕ is a multiplicative constant reflecting the units of measurement. Again, the parameter of primary interest is the exponent, in this case denoted by η, which reflects the over-all shape of the relationship between remembered magnitude and perceived intensity.

In classical psychophysics γ typically ranges from .3 to 3.5, depending on the particular stimulus dimension under investigation and the precise method of measurement. Björkman, *et al.* did not specify the value that η should take, but Kerst and Howard (1978) proposed a model in which the value of η was tightly constrained. In Kerst and Howard's data for perceived and remembered map-distance and map-area, they reported the memory exponent seemed to approximate the square of the analogous perception exponent; that is, for distance they obtained a γ of 1.04 and a η of 1.10 and for area they obtained a γ of .79 and a η of .60. The point of note in these results is that η is approximately equal to γ^2. Kerst and Howard reasoned from this that the same scaling procedures are applied to a stimulus magnitude when that stimulus is recalled as when it is perceived. Thus, a stimulus that is recalled has been scaled twice by γ—once at perception and again at recall. This leads to the more general rule:

$$M = \phi S^{\eta} = \phi (S^{\gamma})^{\gamma} \qquad [3]$$

Kerst and Howard called this idea the *reperceptual hypothesis*.

The reperceptual hypothesis has not gone unchallenged (for a review, see Algom, 1992a). Most attempts to evaluate this hypothesis have used stimulus dimensions with perceptual exponents less than 1 or fairly close to 1, but a much stronger test of the reperceptual notion would involve dimensions for which γ is greater than 1 or more distant from 1. On these dimensions quite large changes are predicted, and the ability of the reperceptual hypothesis model to account for the data would be easier to evaluate. Thus, one purpose of the current experiments is to examine η for two stimulus dimensions with exponents much farther from 1, namely, brightness and loudness. The second, and major, purpose of the current experiments is to evaluate the power function as an appropriate model for memory psychophysics. The power function offers an appropriate description of the relationship between remembered magnitude and physical intensity for some dimensions (e.g., distance, area), and this could be interpreted as offering limited support for the hypothesis of functional equivalence between the processing of perceptions and the processing of images (memories) of those perceptions. Such a viewpoint has been attractive to many theorists (e.g., Farah, 1985, 1988; Finke, 1980; Finke & Shepard, 1986; Hubbard & Stoeckig, 1992; Kosslyn, 1980, 1987) but has not been universally accepted (e.g., Pylyshyn, 1984). While much of the data from studies relating remembered magnitude to perceived intensity seem to be well fitted by power functions (for review, see readings in Algom, 1992b), there are even stronger predictions, based on perceptual research using cross-modality matching, that can be made.

In cross-modality matching, the subject equates sensation magnitudes in two different sense modalities perceived simultaneously (for review, see S. S. Stevens, 1975). Typically, a fixed intensity of a stimulus in one modality is displayed, and the subject produces a stimulus in a second modality that matches the perceived intensity of the stimulus in the first modality. For example, a subject might be asked to adjust the brightness of a light so that the intensity of the light seems to match the intensity of a burst of noise (e.g., Root & Ross, 1965; J. C. Stevens & Marks, 1965). Ignoring for a moment the particular measurement scale constants (λ), then if the two sensations are equated, the following equation should hold:

$$S_a^{\gamma_a} = S_b^{\gamma_b} \quad [4]$$

In essence, when a stimulus in modality S_a is raised to the power γ_a, it will result in the same sensory magnitude as when a stimulus in modality S_b is raised to the power γ_b. Algebraic transformation of Eq. 4 shows that the ratio of the exponents of the two functions, γ_a and γ_b, determines the slope of the cross-modal function when the data have been plotted on logarithmic axes:

$$\log S_a = (\gamma_b/\gamma_a)\log S_b \quad [5]$$

As predicted by Eq. 5, within classical psychophysics the exponent relating the two perceived stimulus dimensions has been found to be a ratio of the exponents relating the perceived magnitude to physical intensity for each dimension when the data have been plotted on logarithmic axes.

Even though the ideas of cross-modality matching have existed for at least 25 years in classical psychophysics (e.g., J. C. Stevens & Marks, 1965), this area of psychophysical theory has not previously been mined for insights about memory representation. If the cognitive processing involved in memory psychophysics is analogous to that involved in classical psychophysics, then subjects should be able to complete a cross-modality matching task in which various intensities of one of the dimensions are perceived and intensities of the other dimension are remembered or imaged. Similarly, subjects should also be able to complete a cross-modality matching task in which the intensities of both stimulus dimensions are remembered or imaged. If functional equivalences between the processing of images and the processing of perceptions exist, then strong predictions can be made concerning the form of the cross-modality matching functions that should obtain when values of one or both of the stimuli are drawn from memory or imaged. Specifically, the relationship between a perceived and a remembered stimulus or two remembered stimuli should be a power function, and the exponent of the power function should approximate the ratio of the remembered or perceived dimensions that are being scaled.

Experiment 1

In this experiment, functions for perceived and remembered brightness, perceived and remembered loudness, and cross-modality matching of imaged brightness/perceived loudness and imaged loudness/perceived brightness were obtained. There were two groups of subjects, a memory group and a perception group. Both groups learned different nonsense syllable names associated with each of five levels of brightness and five levels of loudness. The perception group subjects served as a control condition and provided values for perceived brightness and loudness of the stimuli. The memory group subjects reported magnitudes for remembered brightness and loudness and then completed a cross-modality matching task in which remembered brightness was scaled against perceived loudness and remembered loudness was scaled against perceived brightness. Such a combination of perceptual and memorial elements in the same stimulus is not unprecedented; Algom (1992a) has summarized a number of studies in which subjects created a mental stimulus based in part upon both perceived and remembered information (e.g., the width of the to-be-imaged rectangle was shown and the length of the to-be-imaged rectangle would be specified by some code, e.g., a nonsense syllable name, and subjects would then estimate the total area of the resultant imaged rectangle), a type of stimulus he called *semimental stimuli*. While scaling of semimental stimuli is very useful in examining the way that information from memorial and perceptual sources may be combined, it does not examine the relationship of the remembered and perceived dimensions to each other as directly as a cross-modal comparison.

Method

Subjects.—The subjects consisted of Franklin and Marshall College undergraduates who were recruited from psychology classes and received either partial course credit or a small cash payment in return for participation. All subjects reported possessing normal or corrected-to-normal sight and hearing, and all subjects were naive to the hypotheses until after their data had been collected. Thirty subjects participated in the current experiment; 18 subjects participated in the memory condition and 12 subjects participated in the perception condition.

Apparatus.—During the experiment the subjects were seated in a sound-proof acoustical chamber (Controlled Acoustical Environments, No. 102368). Both brightness and loudness stimuli were synthesized by an Apple Macintosh II microcomputer equipped with an Apple RBG color monitor. The brightness stimuli were displayed directly on the monitor; the loudness stimuli were routed through an amplifier (Physiological Electronics, Inc., White Noise Generator/Amplifier) and presented to subjects over headphones (Bell & Howell, No. 45554). The headphones, amplifier, monitor, keyboard, and mouse were located within the acoustical chamber, and the CPU and disk drives of the Macintosh were located outside the acoustical chamber. The amplifier and monitor were connected to the CPU via cable interfaces through a wall of the acoustical chamber.

Stimuli.—The stimuli were drawn from two dimensions, brightness and loudness. The brightness stimuli consisted of a grey field displayed on the monitor at five levels of varying brightness, as measured by a photometer at a distance of 40 cm from the monitor. The five levels of brightness were .1, 1.6, 11.1, 28.5, and 62 candela/meter^2. The loudness stimuli consisted of tones of 1000 Hz played at loudness levels of 54, 64, 72, 81, and 89 decibels.

Procedure.—To reduce experimenter bias, subjects were run individually by an assistant who was naive to the experimental hypotheses. Subjects were seated facing the monitor at the table inside the acoustical chamber, and the chamber was not illuminated except for the light radiating from the monitor. The experimental procedure was divided into three phases: learning, same-modality scaling, and cross-modality matching. Subjects completed the learning phase first, then proceeded directly to the same-modality scaling phase. After completion of the same-modality scaling phase, subjects in the perception group were debriefed, and subjects in the memory group proceeded directly to the cross-modality matching phase and were debriefed after completion of that phase. Each subject completed the experiment in less than an hour.

In the *Learning* phase subjects saw (heard) each stimulus and learned which nonsense syllable name was associated with each particular stimulus. The procedure was the same for both perception and memory groups. Subjects learned all of the stimulus names for one dimension before proceeding to the second dimension, and order of dimensions was counterbalanced across subjects. One trial consisted of the presentation of each of the five levels of intensity of one of the stimulus dimensions. During the first trial for each dimension, the stimuli were presented in order of increasing intensity and the nonsense syllable associated with each stimulus was printed on the monitor and also spoken aloud by the experimenter. During subsequent trials, stimuli were presented in a different random order on each trial, and the subject had to give the nonsense syllable associated with each of the stimuli. Subjects practiced naming the stimuli in each dimension until they were able to proceed through three consecutive trials (300% overlearning) without making an error.

In the *Same-modality Scaling* phase subjects made a magnitude estimation judgment of the intensity of each stimulus. Subjects in the perception group viewed (heard) each stimulus while making their estimate; subjects in the memory groups were given the nonsense syllable name of one of the stimuli and instructed to base their estimate on a vivid image of what that stimulus looked (sounded) like. The instructions were adapted from samples of standard magnitude-estimation instructions given by S. S. Stevens (1975). No modulus was specified. Order of dimensions was the same as in the learning phase; the order of presentation of stimuli (perception group) or CVCs (memory group) within each dimension was randomly determined.

In the *Cross-modality Matching* phase subjects were shown one of the stimuli and then asked to imagine a stimulus in the other modality that would possess the same level of subjective magnitude as the particular stimulus they were seeing (hearing). They were then instructed to give a number that reflected how intense a stimulus of the nonpresented dimension would have to be to seem as intense as the stimulus they were perceiving. Only memory group subjects participated in this phase. The instructions were adapted from samples of standard cross-modality matching instructions given by S. S. Stevens (1975). No modulus was specified. Order of dimensions was the same as in the learning phase, and the order of stimuli within each dimension was randomly determined. Despite the unusual nature of the task, subjects seemed to not have any trouble understanding what was meant.

Results and Discussion

Three subjects in the memory group used an inverted scale for remembered brightness, that is, they gave smaller numbers to brighter stimuli. The data from these subjects were discarded and not used in any of the subsequent analyses.

The logarithms of physical intensities and subjects' judgments were calculated so that the exponent of the power function (γ in Eq. 1) could be determined more easily. The logic for this is as follows: if the logarithm of each side of Eq. 1 is taken, the resultant equation is of the form

$$\log P = \gamma \log S + \log \lambda \qquad [6]$$

In this form of the equation, γ is now the slope term and may easily be determined by solving for the best-fitting line via least-squares regression.

Perceptual scaling.—The mean response for each intensity level was calculated, and the function relating perceived brightness to physical brightness may be seen in the top panel of Fig. 1 and the function relating perceived loudness to physical loudness may be seen in the bottom panel of Fig. 1. The slope (exponent) of the perceived brightness function is .34 ($r^2 = .99$) and the slope of the perceived loudness function is .51 ($r^2 = .99$). The exponent for

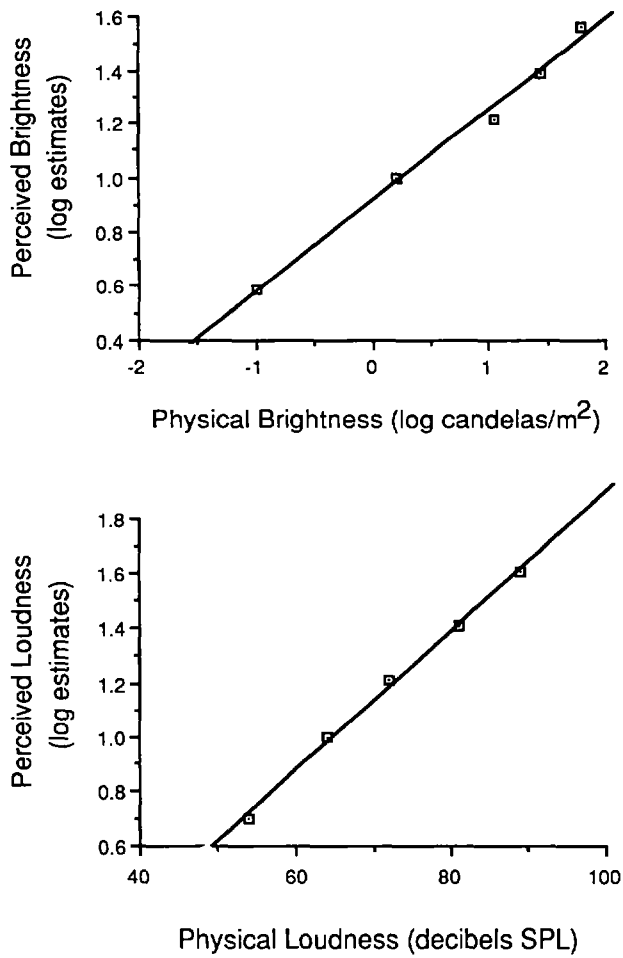

FIG. 1. Perceived magnitude as a function of physical stimulus intensity in Exp. 1. The top panel shows perceived brightness as a function of physical brightness; the bottom panel shows perceived loudness as a function of physical loudness.

perceived brightness is very close to that traditionally reported (e.g., J. C. Stevens & S. S. Stevens, 1963), while the exponent for perceived loudness is slightly higher than that traditionally reported (e.g., S. S. Stevens, 1955) but closer to the values that have been more recently reported (e.g., Ward, 1987). The similarity of the perception group data with that previously published gives confidence that results found in the memory group will be due to the experimental manipulation and not to any idiosyncrasy of the experimental apparatus.

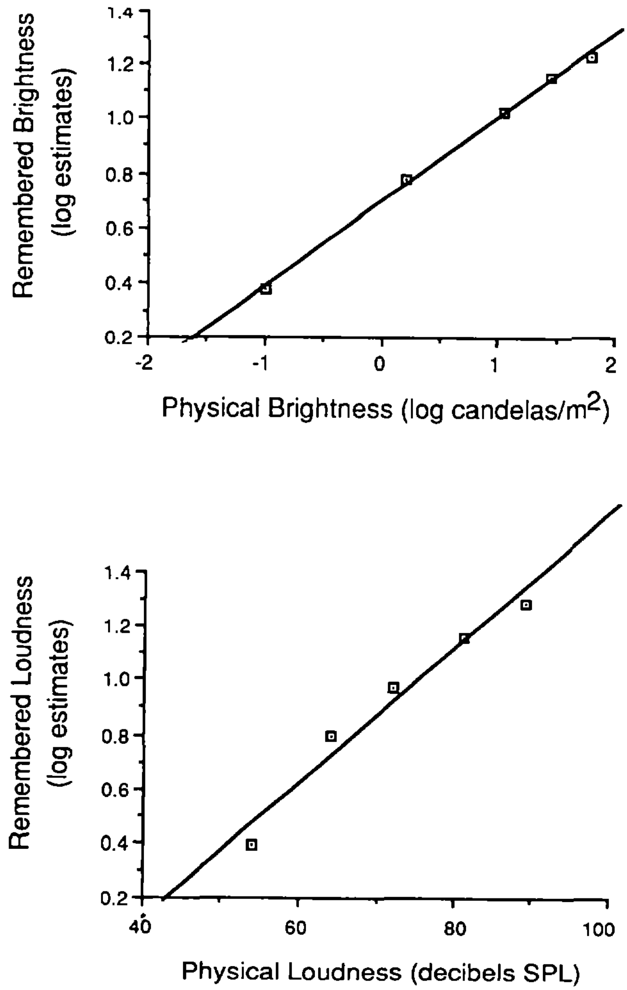

FIG. 2. Remembered magnitude as a function of physical stimulus intensity in the same modality in Exp. 1. The top panel shows remembered brightness as a function of physical brightness; the bottom panel shows remembered loudness as a function of physical loudness.

Same-modality memory scaling.—The mean response for each remembered intensity level was calculated, and the function relating remembered brightness to physical brightness may be seen in the top panel of Fig. 2 and the function relating remembered loudness to physical loudness may be seen in the bottom panel of Fig. 2. The slope (exponent) of the remembered brightness function is .31 ($r^2 = .99$) and the slope of the remembered loudness function is .50 ($r^2 = .96$). These values are nearly identical to those found in the perceptual condition. The reperceptual hypothesis predicts that the exponent for remembered brightness should approximate .12 ($.34^2$) and that the exponent for remembered loudness should approximate .26 ($.51^2$), but exponents calculated for each subject for both brightness ($t_{14} = 9.19$, $p < .0001$) and loudness ($t_{14} = 7.36$, $p < .0001$) were significantly greater than the predicted values.

Cross-modality matching.—The top panel of Fig. 3 shows the relationship between imaged loudness and physical brightness, and the bottom panel of Fig. 3 shows the relationship between imaged brightness and physical loudness. The exponent for imaged loudness/perceived brightness is .30 ($r^2 = .98$), and the exponent for imaged brightness/perceived loudness is .41 ($r^2 = .96$). The functional equivalence idea predicts that the exponent for the cross-modality matching function should approximate the ratio of the remembered and the perceived exponents. For the case of imaged loudness/perceived brightness, the exponent should approximate 1.47 (.50/.34); for the case of imaged brightness/perceived loudness, the exponent should approximate .61 (.31/.51). The individual exponents calculated for each subject for both imaged loudness/perceived brightness ($t_{14} = -59.02$, $p < .0001$) and imaged brightness/perceived loudness ($t_{14} = -5.37$, $p < .0001$) were significantly less than the predicted values.

For brightness, the exponents for all three tasks are approximately equal (for same-modality perception scaling, $\gamma = .34$; for same-modality memory scaling, $\eta = .31$; for cross-modality matching, $\eta = .29$). The same type of pattern is obtained for loudness, as the exponents for all three tasks are approximately equal (for same-modality perception scaling, $\gamma = .51$; for same-modality memory scaling, $\eta = .50$; for cross-modality matching, $\eta = .41$). Even though there was not a great difference in the exponents between the same-modality perception scaling, same-modality memory scaling, and cross-modality matching conditions, it is important to emphasize that the power function seemed to offer an appropriate description of the functions. This finding is consistent with the idea of a weak functional equivalence such that the mental representations in all conditions seem to be scaled in the same way (a power function). While the high r^2 values are consistent with the notion of weak functional equivalence, a good fit of the power function cannot be interpreted as conclusively demonstrating that the underlying functional equivalence model is correct (Parker, Casey, Ziriax, & Silberberg, 1988).

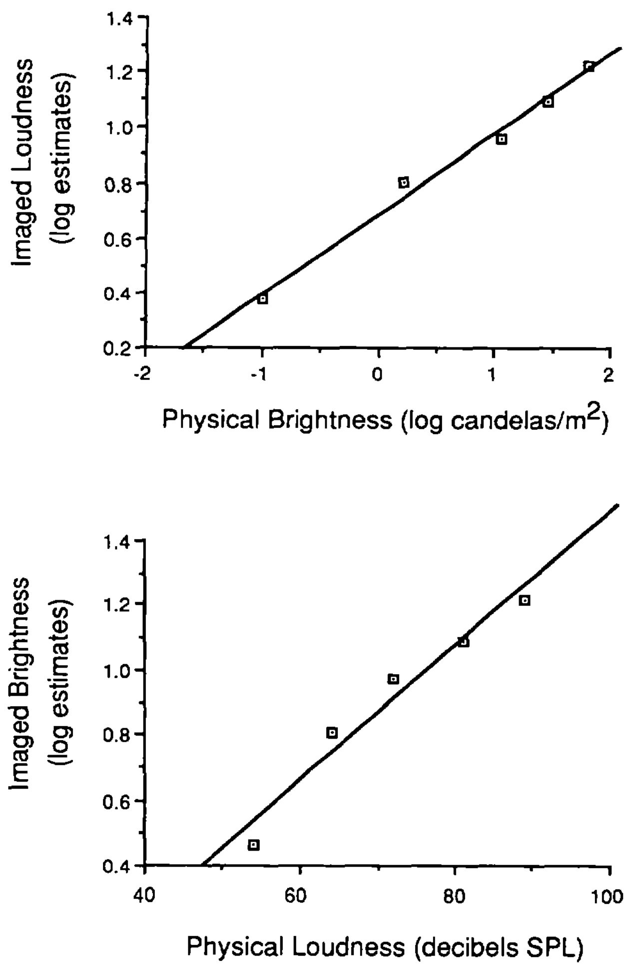

FIG. 3. Remembered magnitude in one modality as a function of physical stimulus intensity in a second modality in Exp. 1. The top panel shows remembered loudness as a function of physical brightness; the bottom panel shows remembered brightness as a function of physical loudness.

For the perception group the display was seen by the subjects and this value assumedly determined the response. For the same-modality memory-scaling task, a mental representation of the display was imaged by the subjects, and the value of the representation of the display assumedly determined the response. In the cross-modality matching task, however, a representation of a stimulus other than that displayed should have been appealed to, that is, subjects' responses were assumedly based on a representation of a stimulus other than that shown on the display, namely, that of a stimulus in the other modality that was equivalent in magnitude to the perceived stimulus. Specifically, if the display was of loudness, their estimation should have been based in part on a brightness image created to match the intensity of the displayed loudness. If the display was of brightness, their estimation was based in part on the loudness image created to match the intensity of displayed brightness. However, subjects may have interpreted "equal subjective magnitude" to mean that because the magnitudes were equal, then cross-modality matching could be based not on a conjunction of perceived and imaged magnitudes, but solely on the perceived magnitudes (located along the x-axis). This idea is discussed in more detail later.

Experiment 2

The previous experiment showed that cross-modality matching techniques could be fruitfully adapted to the study of the mental representation, specifically, to examination of the intensity values portrayed within the memory representation. The current experiment takes this finding one step further and examines the form of the function when subjects compare not just the intensity of a perceived stimulus with the magnitude of a remembered stimulus, but the remembered magnitudes of two different stimuli. To do this, subjects were asked to remember the magnitude of a specific stimulus in one modality and then imagine a stimulus of equal subjective magnitude in a second modality. They then estimated the magnitude of the stimulus in the second modality.

Method

Subjects.—The subjects were drawn from the same pool as in Exp. 1; none of the subjects had participated in the previous experiment. All subjects reported possessing normal or corrected-to-normal sight and hearing, and all subjects were naive to the hypotheses until after their data had been collected. Eighteen subjects participated in the current experiment.

Apparatus and stimuli.—The apparatus and the stimuli were the same as those in Exp. 1.

Procedure.—The procedure also was the same as that in Exp. 1 with two exceptions. First, only a memory group was used. Second, in the cross-modality matching phase, subjects were not shown (played) one of the stimuli and asked to imagine an appropriate stimulus in the other dimension. Instead, they were given the nonsense syllable name of a stimulus, asked to imagine that stimulus, and then asked to imagine a stimulus in the other modality that was of an equal magnitude. Their magnitude estimates were then based on the magnitude portrayed in the second (unnamed) modality.

Results and Discussion

Three subjects used an inverted scale for remembered brightness, that is, they gave smaller numbers to brighter stimuli. The data from these subjects were discarded and not used in any of the subsequent analyses. The exponents for each of the functions were calculated as in Exp. 1.

Same-modality memory scaling.—The data for remembered brightness and remembered loudness are shown in Fig. 4; the top panel shows the function relating remembered magnitude and physical intensity for brightness, and the bottom panel shows the function relating remembered and physical intensity for loudness. The exponent for the remembered brightness function is .35 (r^2 = .99), and the exponent for remembered loudness is .54 (r^2 = .98).

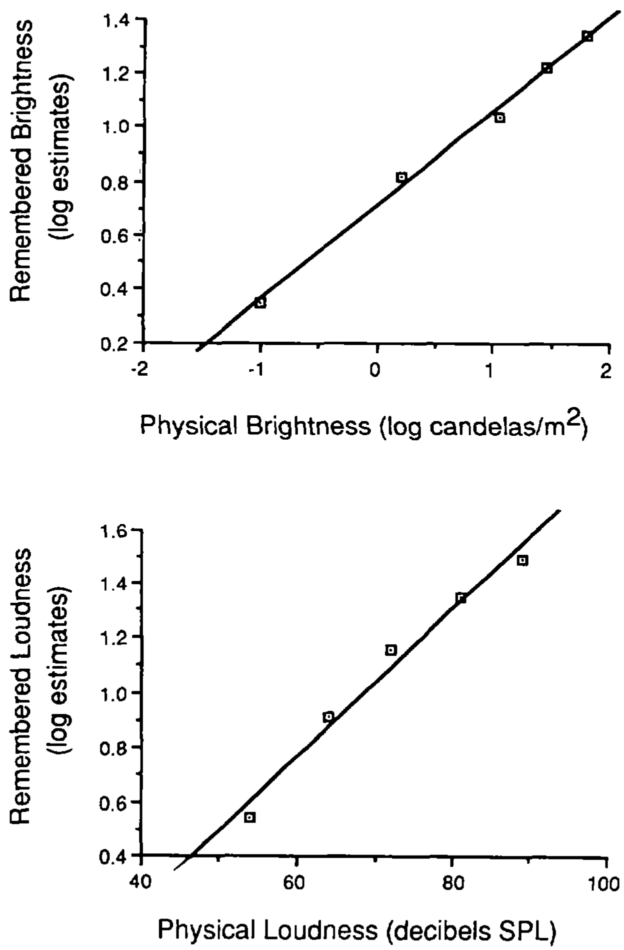

FIG. 4. Remembered magnitude as a function of physical stimulus intensity in the same modality in Exp. 2. The top panel shows remembered brightness as a function of physical brightness; the bottom panel shows remembered loudness as a function of physical loudness.

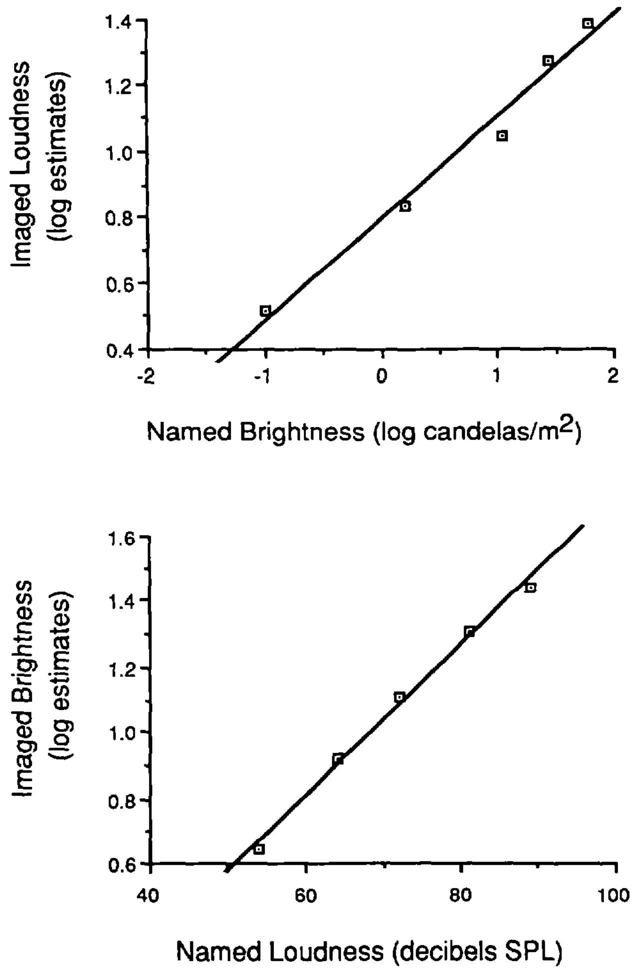

FIG. 5. Remembered magnitude in one modality as a function of named stimulus intensity in a second modality in Exp. 2. The top panel shows remembered loudness as a function of physical (named) brightness; the bottom panel shows remembered brightness as a function of physical (named) loudness.

These values are similar to those found in Exp. 1. The exponents for each subject for each dimension are significantly different from the values predicted by the reperceptual hypothesis ($t_{14} = 9.59$, $p < .0001$ for brightness, and $t_{14} = 6.17$, $p < .0001$ for loudness). As in Exp. 1 the exponents for remembered brightness and remembered loudness do not support the reperceptual hypothesis. One possibility to save the reperceptual hypothesis might be to propose some sort of floor effect such that the squaring function is no longer applied if the stimulus dimension is as contractive as it is for loudness or especially brightness, but such a *post hoc* maneuver seems unprincipled.

Cross-modality matching.—The data from the cross-modality matching tasks are shown in Fig. 5. The functional equivalence idea would predict that the exponent for the cross-modality matching function would approximate the ratio of the remembered exponents. For the case of imaged loudness/named (imaged) brightness, the exponent should approximate 1.54 (.54/.35); for the case of imaged brightness/named (imaged) loudness, the exponent should approximate .65 (.35/.54). The exponents are much lower than the predicted values: for imaged loudness/named brightness the exponent is .31 ($r^2 = .98$), and for imaged brightness/named loudness the exponent is .46 ($r^2 = .99$). The exponents for each subject for both imaged brightness/named loudness ($t_{14} = -10.39$, $p < .0001$) and imaged loudness/named brightness ($t_{14} = -28.07$, $p < .0001$) differ significantly from their predicted values.

As in Exp. 1, the predicted exponents in the cross-modality matching tasks were not obtained. If we compare the functions in the top panels of Figs. 4 and 5 with that in the top panel of Fig. 1, in which physical brightness is plotted on the *x*-axis, similar exponents are found [for same-modality perception scaling $\gamma = .34$ (from Exp. 1); for same-modality memory scaling $\eta = .35$; and for cross-modality matching $\eta = .31$]. If we compare the functions in the bottom panels of Figs. 4 and 5 with that in the bottom panel of Fig. 1, in which physical loudness is plotted on the *x*-axis, similar exponents are again found [for same-modality perception scaling $\gamma = .51$ (from Exp. 1); for same-modality memory scaling $\eta = .54$; and for cross-modality matching $\eta = .46$]. As in Exp. 1, there appears to be little difference between perceived, remembered, and cross-modality matching exponents for either brightness or loudness.

General Discussion

There are three primary empirical contributions. (a) The relationship between remembered brightness and physical brightness and the relationship between remembered loudness and physical loudness are well described by power functions. The values of the exponents of the remembered brightness and remembered loudness functions are very similar to the values of the exponents of the perceived brightness and perceived loudness functions and so do not accord with values predicted from the reperceptual hypothesis. (b) The cross-modal relationship between perceived magnitude in one modality and remembered magnitude in a second modality is well described by a power function. The value of the exponent of the cross-modality matching function is similar to the value of the exponent of the function relating perceived magnitude to physical intensity for stimuli for the perceived dimension. (c) The relationship between a remembered (named) magnitude of stimuli in one modality and the equivalent remembered magnitude of stimuli in a second modality is well described by a power function The value of the exponent of the cross-modality matching function is similar to the value of the exponent of the function relating perceived magnitude to physical intensity for stimuli in the named dimension.

It is curious why the exponents in the cross-modality matching tasks did not reach the values predicted by the notion of strong functional equivalence, but one possibility is that subjects are unable or unwilling to image a stimulus in a modality different from the one they are shown or for which they are told the nonsense syllable name. There are several reasons, however, to doubt this simplistic answer. (a) Subjects seemed to have no difficulty understanding the nature of the cross-modality matching task and what was required of them. (b) During the debriefing the subjects indicated that they had performed the cross-modality matching task as indicated. (c) Other research has shown that subjects can include both visual and auditory components in the same image (e.g., Intons-Peterson, 1980). The inclusion of multimodal information in a single image is also buttressed by common experience; for example, it seems straightforward to recall (image) a recent conversation and include both the face and words of the speaker in the image.

A second possibility why the predicted exponents were not obtained involves the response mode of the subjects. In classical psychophysical studies, cross-modality matching typically involved magnitude production, that is, subjects would adjust the perceived magnitude of one stimulus until it matched the perceived magnitude of a second stimulus. Such adjustment tasks did not require verbal responses on the part of subjects. In the present experiments, however, subjects used magnitude estimation, that is, subjects would give a verbal estimate of the intensity of each imaged stimulus. To examine further the hypothesis that response mode influences subjects' judgments it would be necessary to use a production measure as the dependent variable; use of a production measure, however, would involve perception as the subject would necessarily perceive the magnitude of the modality that was being produced (if by no means other than kinesthetic feedback). It does not seem clear how to utilize a production methodology without letting the subject perceive the magnitude being produced, and it may be that a strict memory-memory cross-modality comparison (such as in Exp. 2) using magnitude production is not possible.

A third possibility why the predicted exponents were not obtained involves domination of the cross-modality function by either the perceived magnitude or the remembered magnitude (or one of the two remembered magnitudes). Previously, Algom, Wolf, and Bergman (1985) demonstrated that exponents obtained with semimental stimuli were closer to memorial values than to perceptual values. Specifically, Algom, *et al.* had subjects learn nonsense syllable names for each of several vertical lines. Subjects were then shown a horizontal line, given the name of one of the vertical lines, and estimated the area of the rectangle formed by the perceived horizontal line and the imaged vertical line. The psychophysical exponent obtained under this condition was closer to the exponent for remembered area than for perceived area, leading Algom, *et al.* to conclude that memorial scale values dominate over perceptual scale values when the two are combined in the same judgment. In Exp. 1, however, the exponent is clearly closer to that of the perceived dimension than that of the remembered dimension, suggesting that perceptual values seemed to dominate over memorial values In Exp. 2, in which stimuli from both dimensions were drawn from memory, the dimension considered first dominated over the dimension that was considered second.

Although the results of Exps. 1 and 2 might seem inconsistent with those of Algom, *et al.* (1985), these inconsistencies might be resolved in several ways. (a) The scaling of Algom, *et al.*'s semimental stimuli involved more holistic comparisons of remembered and perceived area, and not comparisons of the individual components of width and length, whereas Exps. 1 and 2 involved comparison of individual components of loudness and brightness. (b) Algom, *et al.* used stimuli drawn from only the visual modality, but Exps. 1 and 2 utilized stimuli drawn from both visual and auditory modalities. (c) Algom, *et al.* claimed dominance of memory exponents over perceptual exponents based on the compressiveness of the functions they obtained. However, the exponents for perceived brightness and loudness (used in the current experiments) are already more compressive than those for perceived length and area (used by Algom, *et al.*) and thus may already be at a maximum useful compression. In essence, the current data exhibit a floor effect that is not seen in Algom, *et al.*'s data. (d) The subjects in Algom, *et al.* may have completed the memory task first and only after having visualized the vertical length named by the nonsense syllable did they look at the displayed horizontal line. Thus, memory would seem to dominate only because the memorial component of the task was completed first. This sort of strategy on the part of the subjects would be a sensible one as it would minimize confusion about the magnitude of the remembered stimulus that might be caused by viewing the magnitude of the displayed line.

Another possibility for why the exponents did not reach the predicted values involves distinguishing among levels of functional equivalence. Finke (1980) suggests that equivalence in processing between visual images and percepts for any given stimulus dimension depends upon the level of the visual system assumed to be involved in processing that dimension. Finke suggests that, as more higher level cognitive or conceptual processing is required, greater amounts of functional equivalence between perception and imagery are more likely because at higher levels there is a greater opportunity for information-processing to invoke a larger role for preexisting knowledge to modify the use or performance of the representation. In the current experiments, brightness and loudness can be conceived of as relatively low-level processing tasks, and so there may be minimal overlap between perceptual and cognitive (imagery) processes involving stimuli in these two dimensions. Thus, brightness and loudness imagery may be only partially equivalent to perception in the amount or type of cognitive processing involved. This partial equivalence may manifest as a power function relationship, but the equivalence is not complete enough to specify the precise parameters (e.g., exponent) of the function.

While the exponents for the cross-modality matching tasks did not obtain the values predicted from Eq. 5, there is one interpretation of the data in which the cross-modality matching exponents do obtain an expected value. As stated in Eq. 4, when a stimulus in modality S_a is raised to the power γ_a, it will result in the same sensory magnitude as a stimulus in modality S_b raised to the power γ_b. If the sensory magnitudes match, then they will of course result in similar magnitude judgments on the part of the subjects. If a particular brightness possesses a magnitude of 10, then a loudness possessing that same magnitude must also be judged a 10; the magnitude of the comparison stimulus (along the y-axis) will therefore equal the magnitude of the fixed standard stimulus (along the x-axis). If the remembered magnitude of the comparison is equal to the remembered (or perceived) magnitude of the standard, then the relationship between the remembered magnitude of the comparison and physical intensity of the standard is the same as the relationship between perceived (remembered) magnitude of the standard and the physical intensity of the standard. Thus, the exponent of the cross-modality matching function would be determined by which dimension is used as the standard and the exponents for same-modality memory scaling and cross-modality matching would be approximately equal. As pointed out earlier, this was indeed the pattern found.

One area for further investigation is an extension of the idea of cross-modality matching in memory psychophysics to examination of the realm of poetic metaphor and synesthesia. Marks (1982) has documented subjects' use of loudness, brightness, and pitch scales in evaluation of the meanings of various synesthetic expressions (e.g., the sound of coming darkness). In one experiment subjects judged metaphorical expressions on separate scales of loudness and brightness. When visual words modified sound words (e.g., dark cough), the visual words modulated the judged loudness of the sound words, and when sound words modified visual words (e.g., soft moonlight), the sound words modulated the judged brightness of the visual words. Nonetheless, there was far from a complete metaphorical equivalence of brightness and loudness ratings; high values of brightness did not systematically translate into high values of loudness. For example, even though *thunder* was rated as much louder than *whisper, thunder* was not rated as brighter than *whisper.* Even though Marks (1982) collected brightness and loudness ratings for many of the same terms, he did not determine the precise form of the function relating loudness and brightness judgments for those terms.

In conclusion, the use of cross-modality matching techniques in memory psychophysics results in functions similar in form to those found in classical perceptual cross-modality matching tasks, although the exponents obtained are different from those that would be predicted based on classical psychophysical theory. The reasons for this difference remain an area for investigation. The similarity in the forms of the functions offers some limited support for the notion of a partial functional equivalence between the processing of mental images and the processing of perceptual representations. A partial equivalence, rather than a total equivalence, may have been obtained because of the relatively low level of the processing involved in dealing with the brightness and loudness components of the stimuli. At any rate, the adaptation of the cross-modality matching paradigm from classical psychophysics to memory psychophysics seems to yield lawful and useful information about not just mental representations but about the range of psychophysical theory as well.

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