CROSS-MODALITY IN COMPARISONS OF SUCCESSIVE STIMULI

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Two experiments were performed to study effects of modality, temporal position, and their interaction on comparisons of successive stimuli. In Experiment 1, intramodal (tone-tone and line-line) and crossmodal (tone-line and line-tone) stimulus pairs, with two interstimulus intervals (ISIs), were presented. Participants indicated which stimulus was the "stronger." Time-order effects (TOEs) were studied using the classic D% measure as well as weighting coefficients from Hellström's sensation weighting model. TOEs were found in both intramodal and crossmodal comparisons. The classic pause-function (more negative TOE with longer ISIs) was found in all pair types except tone-line. In Experiment 2, participants indicated which of two lines was the longer, or which of two tones was the louder. Intramodal anchors, crossmodal anchors, or no anchors were interpolated between the stimuli. Anchoring tended to yield negative TOEs and to diminish the first stimulus' weight. Intramodal anchoring of tone-tone pairs yielded low stimulus weights, suggesting stimulus interference.

It might seem that comparing two stimuli is possible only in terms of an obviously shared attribute. We can compare a high-pitched and a low-pitched tone for their loudness, or a red and a black line for their length. But can we compare a line and a tone for their magnitude?

Stimulus comparison is not free from complications even with homomodal stimuli, as has been known since the days of Fechner (1860). In the comparison of two successive or simultaneous stimuli, systematic space- and time-order errors (SOEs, TOEs) occur, in that even with identical stimuli observers tend to perceive one as being of greater magnitude than the other. It has been found (Hellström, 1979; Michels & Helson, 1954) that a major clue to understanding TOEs and SOEs is given by considering the perceived stimulus difference not in terms of subtraction, but as generated by a mechanism analougous to linear regression with different weights for the two stimuli. This type of model was elaborated into the *sensation-weighting model* (Hellström, 1979, 1985, 2003), which in its simplified form can be written

$$d_{12} = W_1\ \psi_1 - W_2\ \psi_2 + U, \quad (1)$$

where ψ_1 and ψ_2 are the sensation magnitudes of the compared stimuli, W_1 and W_2 the stimulus weights, and U the intercept.

Crossmodal matching of magnitudes of, for instance, loudness and brightness, has long been practiced (Marks, 1974; Marks, Szczesiul, & Ohlott, 1986) yielding results that can largely be predicted using Stevens' (1957) power law for the matched continua. It has been suggested (Spence, 2011) that stimuli in different sensory modalities can be matched in terms of some amodal feature. It should therefore be of interest to study what happens in the comparison of heteromodal stimuli in the context of a TOE experiment (Exp. 1).

Earlier research (Ellis, 1933; Pratt, 1936) studied the effects of anchor stimuli interpolated between the compared stimuli. The results were interpreted in terms of assimilation of the 1st stimulus to the anchor (Pratt) or contrast of the 2nd stimulus to the anchor (Ellis). Pratt showed that an interpolated low-level anchor yielded a more negative TOE (1st stimulus underestimated relative to 2nd) than a zero-level anchor (i.e., no anchor at all). Oppenheimer et al. (2008) found that anchors in one modality influenced estimates in another modality: Long visual anchors increased numerical estimates of temperature, whereas short anchors decreased them. It is natural to ask what effect crossmodal anchors might have on the TOE. This was here investigated (Exp. 2) using the classic *D%* measure (% '1st greater' - % '2nd greater') as well as SW coefficients W_1 and W_2, for a detailed description of TOEs.

Experiment 1

Method. Participants were 11 men and 38 women aged 18-45 years ($M = 27.5$, $SD = 6.4$). All reported normal hearing and vision. *Apparatus***.** The experiment was run in a sound-attenuated room and controlled by a PsyScope 2.2.5 PPC script (Cohen et al., 1993). Stimuli were presented using a microcomputer with a 27" display unit and calibrated loudspeakers, which were placed on either side of the display unit. Viewing distance was ca 45 cm.

Stimuli. There were 25 tone-tone pairs (1000-Hz), combining five mean sound pressure levels (SPLs), 76.3, 77.1, 77.9, 78.7, and 78.5 dBA with five levels of within-pair SPL difference, ±3.2, ±1.6, and 0 dBA (the same pairs as were used by Hellström, 1979). Similarly, there were 25 line-line pairs, with five mean lengths, 110, 120, 130, 140, and 150 mm, combined with five levels of within-pair difference, ±40, ±20, and 0 mm. There were also 25 tone-line pairs and 25 line-tone pairs, obtained by combining the tone and line stimuli using a common level measure from -4 to +4 (see Table 1).

Procedure. Instructions were displayed, followed by eight familiarization trials, two for each modality combination. Then "Trial:" was displayed for 725 ms, followed by a 250-ms interval until the stimulus pair was presented. Each stimulus had a duration of 250 ms. The pair was followed by "Which stimulus was the stronger?" – to be taken as generic stimulus strength. Three adjacent keys were used, labelled "first," "second," and "same." Each block was made up of a set of 25 stimulus pairs, presented twice; the set was first presented in pseudorandom order with a 400-ms ISI and then in another order with a 2000-ms ISI. The intertrial interval was, with equal probability, 1000 ms or 2000 ms. Before each block the participants were notified of the modal combination. There were four block orders; the two intramodal blocks always preceded the two crossmodal blocks, for familiarization with the stimulus ranges. The four block orders were distributed evenly across participants.

*Results***.** Crossmodal TOEs are not 'errors,' as there is no objectively 'true' match between a line length and a tone loudness, but they may show up as effects of ISI or modal order on *D%* as well as *W* values. The subjective stimulus difference (d_{12}), was estimated by scaling the responses: *first* = +100, *second* = -100, *equal* = 0. The mean d_{12} value for all the stimulus pairs was interpreted as the classic percent difference (*D%*) measure. For each participant and condition, the data were submitted to the SPSS procedure Regression, independent variables being the 1st and the 2nd stimulus level (-4 to +4), and the dependent variable being d_{12}. The standardized (β) coefficients were interpreted as *W* values in the simplified SW model (Equation 1). The results are presented in Table 1.

Percent difference (D%). The *D%* values were submitted to a 2 x 2 x 2 repeated measures ANOVA. The factors were modality of 1st stimulus, modality of 2nd stimulus, and ISI (400 or 2000 ms). There was an effect of the 1st modality, $F(1,48) = 5.473$, $p = .024$, $\eta^2_p = .102$: $D\%_{\text{line}} < D\%_{\text{tone}}$. There was also an effect of the ISI, $F(1,48) = 50.368$, $p < .001$, $\eta^2_p = .512$: $D\%_{2000\text{ ms}} < D\%_{400\text{ ms}}$ (the exception being tone-line, reflected by interactions).

W values. The *Ws* were submitted to 2 x 2 x 2 repeated measures ANOVAs. The factors were modality (tone-tone or line-line for intramodal; tone-line or line-tone for crossmodal), temporal position (1st or 2nd), and ISI (400 ms or 2000 ms). For the *intramodal pairs* there was an effect of modality, $F(1,48) = 30.583$, $p < .001$, $\eta^2_p = .389$: $W_{\text{line-line}} > W_{\text{tone-tone}}$, and also effects of ISI, $F(1,48) = 10.119$, $p = .003$, $\eta^2_p = .174$, $W_{2000\text{ ms}} > W_{400\text{ ms}}$, and of position, $F(1,48) = 5.094$, $p = .029$, $\eta^2_p = .096$, $W_1 < W_2$. Modality x Position x ISI interacted, $F(1,48) =$

Table 1. *Experiment 1. Stimulus Pairs, Indicating Mean Level and Level Difference*

1st stimulus Level	dBA	mm									
4	81.1	170					2/4				
3	80.3	160				1/4		2/2			
2	79.5	150			0/4		1/2		2/0		
1	78.7	140		-1/4		0/2		1/0		2/-2	
0	77.9	130	-2/4		-1/2		0/0		1/-2		2/-4
-1	77.1	120		-2/2		-1/0		0/-2		1/-4	
-2	76.3	110			-2/0		-1/-2		0/-4		
-3	75.5	100				-2/-2		-1/-4			
-4	74.7	90					-2/4				
		dBA	74.7	75.5	76.3	77.1	77.9	78.7	79.5	80.3	81.1
		mm	90	100	110	120	130	140	150	160	170
		Level	-4	-3	-2	-1	0	1	2	3	4
							2nd stimulus				

10.424, p = .002, η^2_p = .178. For the *crossmodal pairs* Position had a significant effect, $W_1 < W_2$, $F(1,48)$ = 24.258, p < .001, η^2_p = .336. Position x ISI interacted, $F(1,48)$ = 18.854, p < .001, η^2_p = .282, as well as Modality order x Position, $F(1,48)$ = 6.915, p = .011, η^2_p = .126.

Discussion. In the SW model, a W value is interpreted as reflecting the amount of information obtained from the stimulus in the comparison (Hellström, 1985; Patching, Englund, & Hellström, in press). Line-line yielded higher Ws than tone-tone. This may be due to the lines being easier to discriminate. A general effect of temporal position was found ($W_1 < W_2$) – here implying that TOEs exist also in crossmodal comparisons. For $D\%$, except for tone-line, there was an effect of ISI: the longer ISI yielded more negative $D\%$s (the classic p-function). The results indicate that TOEs do occur in crossmodal comparisons, and suggest that the process of comparing two stimulus magnitudes is to some extent amodal, that is, involves general magnitude processing, independent of sense modality.

Experiment 2

Method. Participants were 15 men and 33 women (M_{age} = 28, SD_{age} = 8.2). All reported normal hearing and vision. The *apparatus* was the same as in Exp. 1. The *task* was to judge which of two lines was the longer, or which of two tones was the louder. The *design* had six blocks: two blocks without anchors and four blocks with an interpolated anchor between the stimuli; in two blocks this was of the same modality as the compared stimuli and in two blocks it was of a different modality. The anchor had two levels: high and low. *Stimuli.* The basic design was the same as in Exp. 1 (Fig. 1). There were 25 line-line pairs, combining five levels of line-length difference (±20, ±10, and 0 mm; in terms of level, ±4, ±2, 0) with five mean line lengths (95, 100, 105, 110, and 115 mm; in terms of level, ±2, ±1, 0). The lines were black on a white background. There were also 25 tone-tone (1000 Hz) pairs, with five SPL differences (±3.2, ±1.6, and 0 dBA) in combination with five mean SPLs (68.4, 69.2, 70.0, 70.8, and 71.6 dBA). There were also 25 tone-line pairs and 25 line-tone pairs, obtained by combining the line and tone stimuli to the same level differences and mean levels as for the

Table 2. *Experiment 1. Mean % Correct, D%, Mean W_1, Mean W_2 (*SD*s in Parentheses)*

1st stim.	ISI ms	2nd stim.	% Correct	% "Equal"	*D%*	W_1	W_2
Tone	400	Tone	67.8	39.1	5.55 (77.9)	0.50 (0.20)	0.48 (0.16)
Tone	2000	Tone	71.2	36.6	-13.14 (78.6)	0.50 (0.14)	0.58 (0.18)
Tone	400	Line	70.0	29.6	-2.20 (83.9)	0.44 (0.20)	0.56 (0.14)
Tone	2000	Line	71.2	31.3	-0.41 (82.9)	0.41 (0.20)	0.63 (0.14)
Line	400	Tone	72.2	26.4	-5.06 (85.7)	0.55 (0.13)	0.47 (0.22)
Line	2000	Tone	67.3	31.0	-15.76 (81.6)	0.46 (0.21)	0.53 (0.20)
Line	400	Line	93.4	15.8	-1.22 (91.8)	0.56 (0.15)	0.61 (0.08)
Line	2000	Line	85.0	24.9	-11.43 (85.9)	0.62 (0.09)	0.62 (0.07)

line-line and tone-tone pairs. The short and long line anchors were 75 and 135 mm; the soft and loud tone anchors were 63.4 and 76.4 dBA.

Procedure. Instructions were displayed: "You are to compare line-lengths and tone-loudnesses. In one block you will compare two line-lengths presented sequentially, and you are then to state which line was the longer. In a second block you are to compare two tone-loudnesses presented sequentially, and you are then to state which was the louder. Other blocks are similar except there will be an additional stimulus (either line or tone) between the stimuli in the pair. You are to compare the first and the last stimulus and ignore the interpolated stimulus." There were 6 practice trials (one from each block). The command "Be prepared:" was displayed for 725 ms followed by a 250-ms interval until either a stimulus dyad or triad was presented, followed by "Which line was the longer?" or "Which tone was the louder?". Three adjacent response keys were labeled "first," "same," and "last." The participants were to press "same" if they could not find another answer. Each stimulus lasted 150 ms, and the interval before and after the anchor stimulus was 1000 ms. Thus the ISI between the compared stimuli was 2150 ms (also with no anchor). The intertrial interval alternated pseudorandomly between the two values, 500 and 1000 ms. Before each block the participant was notified, for example, "You will now compare two line-lengths with a tone presented in between." The blocks and the anchor levels were presented in pseudorandom orders. The two blocks with no anchor always came first.

Results. The subjective difference score, d_{12}, was estimated as in Exp. 1. The data for each participant and condition were submitted to SPSS Regression. The independent variables were the level (-4 – +4) of the 1st and the 2nd stimulus; the dependent variable was d_{12}. The standardized regression coefficients (β values) were interpreted as *W*s in the simplified SW model (Equation 3). The results are presented in Table 3.

Anchor effects on D%. Repeated-measures ANOVAs with multivariate tests were conducted to compare the TOE measure *D%* in the five anchoring conditions. For *tone-tone D%* differed across anchoring conditions, $F(4,44) = 3.550$, $p = .014$, $\eta^2_p = .244$: *D%* was lower with all anchors than with the null anchor (soft tone, $p = .046$; loud tone, $p = .009$, long line, $p = .001$, short line, $p = .016$). An ANOVA of the *anchored* tone-tone conditions yielded no significant results.

For *line-line D%* differed across conditions, $F(4,44) = 11.526$, $p < .001$, $\eta^2_p = .512$. *D%* was more negative with the short line anchor than with the null anchor, $p < .001$. For the *anchored line-line* conditions there were effects of anchor level, $F(1,47) = 12.265$, $p = .001$, $\eta^2_p = .207$: $D\%_{low}$ (-17.347) < $D\%_{high}$ (-16.042); and of anchor modality, $F(1,47) = 16.971$, $p < .001$, $\eta^2_p = .265$: $D\%_{line}$ (-18.917) < $D\%_{tone}$ (-14.472). Anchor level x Anchor

Table 3. Experiment 2. Obtained TOE Measures

1st stimulus	Anchor	2nd stimulus	% correct	% "same"	Mean *D%* (*SD*)	Mean W_1 (*SD*)	Mean W_2 (*SD*)
Tone	None	Tone	76.8	30.8	4.41 (83.1)	0.53 (0.12)	0.61 (0.10)
Tone	Soft tone	Tone	49.1	51.9	-2.25 (69.3)	0.05 (0.23)	0.02 (0.27)
Tone	Loud tone	Tone	48.6	54.7	-5.60 (81.8)	-0.03 (0.24)	0.09 (0.25)
Tone	Short line	Tone	75.3	27.5	-3.50 (85.1)	0.49 (0.11)	0.62 (0.12)
Tone	Long line	Tone	75.1	27.3	-2.00 (85.3)	0.44 (0.14)	0.65 (0.11)
Line	None	Line	77.5	26.9	-12.08 (84.7)	0.57 (0.13)	0.57 (0.14)
Line	Soft tone	Line	70.25	35.1	-12.18 (93.3)	0.48 (0.16)	0.58 (0.14)
Line	Loud tone	Line	70.4	33.75	-9.92 (80.8)	0.46 (0.15)	0.58 (0.14)
Line	Short line	Line	68.5	31.25	-26.08 (78.7)	0.44 (0.20)	0.53 (0.14)
Line	Long line	Line	67.8	33.5	-10.83 (80.9)	0.39 (0.16)	0.58 (0.14)

modality interacted, $F(1,47) = 11.715$, $p < 0.001$, $\eta^2_p = .200$.

Discriminability. As an index of discriminability, the values of $M_W = (W_1 + W_2)/2$ were submitted to repeated measures ANOVAs. For *tone-tone*, M_W differed across the five anchoring conditions, $F(4,44) = 112.224$, $p < .001$, $\eta^2_p = .911$. The tone anchors yielded worse discriminability than the null anchor, *p*s < .001. For *line-line*, M_W likewise differed across the five conditions, $F(4,44) = 4.329$, $p = .005$, $\eta^2_p = .282$. M_W was larger for the null anchor than for the soft-tone anchor, $p = .025$, the loud-tone anchor, $p = .005$, the short-line anchor, $p = .001$, and the long-line anchor, $p < .001$.

Weighting balance. As an index of weighting balance, the values of $W_1 - W_2$ were submitted to repeated measures ANOVAs. For *tone-tone*, $W_1 - W_2$ differed across the five anchoring conditions, $F(4,44) = 7.705$, $p < .001$, $\eta^2_p = .412$. For the soft-tone anchor, $W_1 - W_2$ was greater (positive) than with the null anchor, $p = .023$, and with the long-line anchor it was more negative, $p < .001$. For *line-line*, $W_1 - W_2$ differed across the five conditions, $F(4,44) = 5.070$, $p = .002$, $\eta^2_p = .315$. For all *anchored* conditions $W_1 - W_2$ was negative (*p*s < .02), whereas with the null-anchor it was zero.

Discussion. For *line-line*, the low-level intramodal anchors yielded more negative *D%* than the null-anchor, in accordance with Pratt (1936). The crossmodal soft-tone anchor did not exert the same pull as the intramodal short-line anchor. Also, an intramodal anchor generally yielded lower *W* values than a crossmodal anchor. This suggests that crossmodal anchors do not interfere with the comparison process as much as intramodal anchors.

The tone-anchored *tone-tone* conditions had very low *W*s, few correct responses (ca 32%), and high percentages of "same/don't know" answers (ca 50%). There were also low *D%* values and much smaller TOEs than in the other conditions. Thus, a tone anchor drastically impaired tone discrimination. This suggests that the anchor blocked the memory of the 1st tone and/or distracted attention to the 2nd tone. As this effect was much weaker for the line-anchored *line-line* conditions, it suggests different mechanisms for discriminating between auditory and between visual stimuli.

For *tone-tone*, W_1-W_2 was more negative with the crossmodal (visual) anchor than with the intramodal (auditory) anchor or the null anchor. Conversely, for the line-line comparison W_1-W_2 was less negative with the crossmodal (auditory) anchor than with the intramodal (visual) anchor, but more negative than with the null anchor. In accordance with Oppenheimer et al. (2008) the results show that anchors in one modality can influence comparisons of stimuli in another modality.

General Discussion and Conclusion

Our results show that it is indeed possible to compare a tone and a line for their ”strength,” and that TOEs show up in these comparisons. Likewise, an interpolated anchor of another modality can affect comparisons of successive stimuli. Generally, an intra- as well as crossmodal anchor rendered W_1-W_2 more negative, which may be due to interference with memory of the 1st stimulus. The drastic effect in the direction of a more negative TOE of interpolating a short line in line-line comparison is in line with Pratt (1936): The decrease in W_1, rather than increase in W_2, suggests retroactive assimilation rather than proactive contrast. According to SW theory, assimilation should increase with the reduction of W_1 (Hellström, 1985). No corresponding effect was found with crossmodal anchors. However, for tone-tone comparisons, all anchors changed the TOE (*D%*) from positive to negative. This might be due to assimilation to a softer reference level, as conceived in the full version of the SW model (Hellström, 2003; Patching, Englund, & Hellström, in press).

Author Note

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