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The Effects of Acoustic Intensity, Spectrum, and Duration on Global Loudness Change

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Summary
Global loudness change is a post-stimulus retrospective judgement that measures listeners' overall impressions of loudness change in response to stimuli with continuous increases (up-ramps) and decreases (down-ramps) of acoustic intensity that are otherwise acoustically identical. Past results indicate that global loudness change is significantly greater in response to up-ramps relative to down-ramps for tonal stimuli (e.g., vowel) but not white-noise. An adaptive perceptual bias for up-ramp tonal stimuli has been proposed as a functional ecological explanation. However, global loudness change may also be influenced by stimulus duration and an end-level recency-in-memory mechanism that biases retrospective global judgements on a ramp's end-level intensity, rather than its entire magnitude of intensity change. The present within-subjects experiment ($N = 34$) was designed to systematically investigate the effects of intensity, spectrum, and duration on global loudness change when end-level recency is controlled. Up-ramps and down-ramps were embedded within two spectral conditions (tonal vowel /ə/ and white-noise) and presented over three durations (1.8 s, 3.6 s, 7.2 s) and two regions of intensity change (45–65 dB SPL, 65–85 dB SPL). End-level recency response bias was controlled through the use of balanced end-level comparisons between 45–65 dB SPL up-ramps and 85–65 dB SPL down-ramps that both converged on 65 dB SPL. Overall, global loudness change was significantly greater in response to vowel and white-noise up-ramps, relative to their corresponding down-ramps. However, with end-level recency controlled, global loudness change was significantly greater for up-ramps relative to down-ramps in 3.6 s and 7.2 s vowel conditions only. This was facilitated by an up-ramp-specific effect of duration, where the magnitude of global loudness change increased as vowel up-ramp duration increased from 3.6 s to 7.2 s. The findings are discussed in the context of psychoacoustics and ecological acoustics.

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1. Introduction

Loudness is the psychological attribute of auditory sensation most closely related to a sound's physical intensity. In real-world listening domains such as speech and music, acoustic intensity and loudness dynamically change through time and significantly influence a range of everyday perceptual experiences on a moment-to-moment basis [1]. It is not surprising, therefore, that psychoacoustic experiments investigating the relationship between intensity and loudness have increasingly addressed the issue from a dynamic standpoint, measuring perceived *changes* in loudness in response to stimuli comprising continuous increases (up-ramps) and decreases (down-ramps) of acoustic intensity. Several paradigms have been implemented to measure loudness change using direct and indirect methods (for a review, see [2]). To summarise here, *indirect* loudness change has been calculated from magnitude estimates of loudness at the onset, offset, and sometimes intermittently throughout a dynamic intensity sweep. In this paradigm, loudness change in its simplest form is calculated as the ratio between two discrete onset/offset loudness magnitude 'snapshots'. For pure-tone stimuli presented at durations from ∼10 s to 180 s, the ratio between onset and offset loudness magnitude ratings (an 'indirect' index of loudness change) for a down-ramp falling from a relatively high sound pressure level (SPL) to approximately 40 dB SPL and below is greater than for a corresponding up-ramp matched on all other acoustic parameters [3]. This phenomenon has been termed decruitment [3, 4, 5, 6], defined as the accelerated loss of loudness in response to a sound that continuously decreases in level (also termed 'sweep induced fading' [6]). Down-ramp sensory adaptation has been proposed as a candidate mechanism [3].

Similar to the effects of psychophysical forward masking, the adaptation hypothesis suggests that early and relatively high intensity portions of the down-ramp adapt neurons and, as a result, the later end-level portion of the down-ramp becomes less audible and perceptually

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‘softer’ in loudness than the equivalent end-level intensity presented in isolation of a preceding down-ramp [3, 7]. Early and relatively low-intensity portions of an up-ramp may not cause substantial adaptation for later higher-intensity portions. Thus, the magnitude of loudness change is greater in response to down-ramps, relative to up-ramps, most likely because of a down-ramp end-level loudness ‘softening’ effect. This explanation for down-ramp decruitment has received support in a relatively complex auditory context where up-ramps and down-ramps of intensity were embedded in short melodies [8]. However, whether sensory adaptation is the underlying mechanism is yet to be determined, and it is clear that cognitive factors such as directed attention make a significant contribution to the magnitude of decruitment [9].

Conflicting results to down-ramp decruitment have been reported in experiments measuring a *direct* post-stimulus ‘global’ judgement of loudness change. Neuhoff [10] measured global loudness change in response to 1.8 s up-ramps and down-ramps with a 15 dB dynamic range, presented as 1 kHz pure-tone, white-noise, or vowel stimuli (/ə/ – sounds like the ‘a’ in ‘about’). Results indicated that the simple pure-tone and complex tonal vowel up-ramps were perceived to change significantly more in loudness than their corresponding down-ramps. However, no significant differences between up- and down-ramps were observed for white-noise. An adaptive perceptual bias for rising intensity was proposed as a functional ecological (but not mechanistic) explanation of these results [10, 11, 12, 13]. As continuous increases of acoustic intensity are a vital cue for perceiving looming (approaching) auditory motion [14], the adaptive perceptual bias predicts that an overestimation of global loudness change for up-ramp tonal stimuli may function as a survival response akin to those reported in time-to-contact experiments (e.g. [12, 15, 16]), where the time to contact of a looming object with the listener is perceived to occur sooner than would be predicted by the physical velocity of the approaching stimulus. This bias effectively allows extra time for an organism to ‘err on the side of caution’ when taking appropriate action (e.g., avoidance or retreat) [10, 12]. Furthermore, according to Neuhoff, tonal stimuli are associated with single sound sources and elicit ‘perceptually salient’ responses relative to dispersed sound sources associated with white-noise (e.g., crowd noise, rain, wind [10]). Multiple sound sources should not necessarily demand equivalent behavioural priority when compared to simple (pure-tone) and complex (vowel) tonal stimuli.

However, the assertion that looming and potentially threatening single sound sources in the environment are characterised by tonal spectra is yet to be substantiated. Indeed, this evolutionary argument is a somewhat oversimplification of our environment. For example, dispersed sound sources such as a gale-force wind sweeping through trees or the crash of waves in the Great Southern Ocean are certainly spectrally similar to white-noise. However, a fast-approaching predatory animal or a large boulder rolling down a slope towards an unsuspecting victim will also contain spectral information that is more similar to noise rather than tones. This example is but one limitation of an evolutionary explanation for the ‘up-ramp perceptual bias’ when tonal versus noise distinctions are made in the context of single versus multiple sound sources (see [17] for further discussion on potential shortcomings of the adaptive ‘perceptual bias for rising intensity’ hypothesis).

Neuhoff [18] also argued that a direct global judgement of loudness change in response to an up-ramp looming stimulus in the environment is more useful for localising a moving sound source than snapshot judgements of loudness used in magnitude estimation experiments. However, there is now evidence that differences in global loudness change between up-ramps and down-ramps may reflect a recency response bias, where a listener’s global perception of loudness change is nonconsciously biased by end-level intensity, rather than the dynamic stimulus characteristics of interest such as magnitude of intensity change [6, 19, 20, 21, 22, 23]. In simple terms, recency is defined as a memory-related recall bias for the last item presented in a sequence of stimuli [24]. As retrospective global judgements of perceived change are made up to many seconds after the onset and duration of a sweep, a listener’s response could unwittingly be confused with perception of stimulus end-level. This is due to memory limitations biasing the retrospective judgement on the most recent portion of the sound: its end-level. If a post-stimulus retrospective judgement of perceived loudness change is strongly weighted on the most recent portion of the stimulus – the end-level – and not necessarily the magnitude of intensity change, then it is not surprising that retrospective global judgements of loudness change are greater for up-ramps because in experiments, up-ramp end-level is usually greater than down-ramp end-level (e.g., 70–90 dB SPL up-ramps compared to 90–70 dB SPL down-ramps – a 20 dB end-level difference).

This end-level recency bias hypothesis was investigated by Olsen *et al.* [20], where end-level recency was controlled by balancing end-level differences in an analysis comparing 50–70 dB SPL up-ramps with 90–70 dB SPL down-ramps using the /ə/ vowel stimulus at 1.8 s and 3.6 s ramp durations. In this analysis, both up-ramp and down-ramp end-levels were equivalent (70 dB), hence the term ‘balanced end-level’ analysis. The original perceptual bias for rising intensity reported in the context of global loudness change [10] was not observed when end-levels of 1.8 s up-ramps and down-ramps were equivalent. This result provides evidence that previous differences between up-ramps and down-ramps [10] can be explained by an end-level recency response bias. However, global loudness change was significantly greater for 3.6 s up-ramps relative to 3.6 s down-ramps when end-level recency was controlled [20]. This up-ramp-specific effect of duration on global loudness change is yet to be explained or systematically investigated. The present study aimed to replicate and extend the global loudness change experiments of Neuhoff [10] and Olsen *et al.* [20] to further investigate: (1) end-level recency as an explanatory cognitive mechanism underlying differences in global loudness change between up-ramps and down-ramps; and (2) the temporal characteristics of an up-ramp-specific effect of duration on global loudness change.

One tonal stimulus (the /ə/ vowel) and one noise stimulus (white-noise) comprised the spectrum independent variable in a 2 × 2 × 2 × 3 within-subjects factorial design. Furthermore, two directions of intensity change (up-ramp, down-ramp) were presented in two regions of intensity change (low 45–65 dB SPL, high 65–85 dB SPL). The use of two regions of change also enabled balanced end-level comparisons between up-ramps and down-ramps that controlled end-level recency (i.e., low region up-ramps compared with high region down-ramps, both with end-levels of 65 dB SPL). These stimuli were presented over three durations (1.8 s, 3.6 s, 7.2 s) to investigate the time-course of the previously reported up-ramp-specific effect of duration [20]. In addition, steady-state white-noise and vowel 'control' conditions were presented over all three durations with 45, 65, and 85 dB SPL steady-state intensity profiles. The dependent variable was a single post-stimulus global judgement of loudness change.

Following Neuhoff [10], no differences in global loudness change between white-noise up-ramps and down-ramps were predicted. In regards to global loudness change in response to vowel conditions, it was hypothesized that:

1. Global loudness change is greater for vowel up-ramps relative to down-ramps in both low and high regions of intensity change, but not for white-noise;
2. Global loudness change is greater in response to vowel up-ramps relative to down-ramps at each stimulus duration, but not for white-noise;
3. In a balanced end-level analysis, global loudness change is greater in response to 45–65 dB SPL low-region vowel up-ramps relative to 85–65 dB SPL high-region vowel down-ramps within 3.6 s and 7.2 s conditions, but not 1.8 s conditions or white-noise conditions.

2. Method

2.1. Participants

The sample consisted of 34 adult participants recruited from the University of Western Sydney (29 females and 5 males; M = 20.26 years, SD = 3.83, Range = 18–35 years). All reported normal hearing and received course credit for participation.

2.2. Stimuli and equipment

All dynamic stimuli followed a linear level increase (up-ramp) or decrease (down-ramp) between 45–65 dB SPL for the low region of change and between 65-85 dB SPL for the high region of change. The generation of the vowel stimuli began with 1.8 s, 3.6 s, and 7.2 s steady-state vowels (/ə/; $F_0 = 130.8$ Hz) from a Klatt synthesizer [25][1] using the default sampling frequency of 8 kHz. Initial white-noise steady-state stimuli were generated in Audacity (Version 2.0.2). Intensity manipulations were constructed from these steady-state exemplars in a sound-attenuated booth. Sennheiser HD25 headphones were calibrated to produce the correct minimum and maximum unweighted levels for each region of change within a custom computer program written in MAX-MSP (Version 4.6.3). This calibration was achieved by a Brüel and Kjær Artificial Ear 4152 attached to a Brüel and Kjær Hand-Held Analyser 2250 using Sound Level Meter Software BZ-7222. The MAX-MSP program then created linear level changes for all up-ramp and down-ramp stimuli from the calibrated minimum and maximum levels for each region of change. This method of stimulus construction ensured that no other acoustic properties were varied and that level changes were created in the 'digital domain' to avoid artifacts from extraneous variables (e.g., ambient low-frequency noise). The new dynamic stimuli were imported into Audacity and a 10 ms linear fade-in and fade-out was incorporated to remove any onset/offset clicks. The steady-state conditions used in the experiment were measured and created in an identical manner to ramped stimuli, but did not vary in intensity between onset and offset.

An additional 2 s steady-state orientation stimulus was spliced to the beginning of each trial and was separated from the main stimulus (i.e., up-ramp, down-ramp, or steady-state control) with 500 ms of silence (a silent duration long enough to avoid possible forward masking effects on perception of the main stimulus [7, 26]). The purpose of the orientation stimulus was to prepare the listener for the beginning of the trial and to avoid the potential for a startle response to the main stimulus, especially in relatively high-intensity conditions. The inclusion of an orientation stimulus has previously been shown to have no significant differential effects on perception of up-ramps and down-ramps when compared to experimental conditions that do not contain an orientation stimulus [6]. Similar to the design in [21], the orientation stimulus in each trial had the same intensity as the onset of the main stimulus and the same spectrum (here, either vowel or white-noise). Therefore, each trial consisted of a 2 s orientation stimulus, 500 ms silence, and a main stimulus that comprised either an up-ramp, down-ramp, or steady-state intensity profile presented over durations of either 1.8 s, 3.6 s, or 7.2 s.

The experiment was conducted in a sound attenuated booth and stimuli were presented diotically using an Edirol UA-25 external USB soundcard. Although diotic headphone presentation can result in the internalisation of perceived changes of distance and motion, listeners can still perceive apparent motion in response to up-ramps and down-ramps in this listening context [27, 28]. The presentation of the experiments was accomplished using a custom written Java application that displayed the vertical loudness-change scale on the computer monitor (spatial extent = 110 mm). The scale ranged from 0–100 representing 'no-change' in loudness to 'large-change' in loudness, respectively, with 'moderate change' displayed as the

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[1] See <http://www.asel.udel.edu/speech/tutorials/synthesis/vowels.html> for the Klatt vowel synthesis interface and [7] for detail and illustration of the /ə/ vowel spectra.

midpoint of the scale. The scale numbers were not visible to participants.

2.3. Procedure

Participants first read an experiment information sheet, gave written informed consent, and received standardised instructions regarding the task. Participants were instructed to focus on the magnitude of loudness change within the main stimulus and make a single judgement of loudness change on the scale as quickly and accurately as possible after stimulus offset. Eight practice trials using a 1 kHz pure-tone with a range of intensity and duration combinations were first presented for participants to become accustomed to the task. The main experiment trials were divided into four fully randomised blocks of all 42 conditions comprising all combinations of each variable including steady-state conditions (but not including practice trials). Consequently there were a total of 168 trials – four presentations of each condition. A demographic questionnaire was administered after the second block of trials and the experiment took approximately 40 minutes to complete.

2.4. Data analysis

Repeated-measures analysis of variance (ANOVA) was the primary statistical technique used to investigate each hypothesis. Where applicable, post-hoc pair-wise comparisons were made using a series of t-tests with significance determined by the Hochberg correction for multiple testing [29]. When the assumption of sphericity was not met using Mauchly's test of sphericity, Greenhouse-Geisser corrections were implemented and corresponding epsilon values are reported. Partial eta squared (η_p^2) is reported as a measure of effect size [30].

To provide an overview of the complete data set, we first present results from a full 2 × 2 × 2 × 3 repeated measures ANOVA including spectrum, intensity direction, intensity region, and duration independent variables. Each hypothesis is then addressed for vowel and white-noise conditions separately through two 2 × 2 × 3 repeated measures ANOVAs including intensity direction, intensity region, and duration independent variables. This is followed by results of the steady-state control conditions.

3. Results

For an overall summary of results, Table I provides descriptive statistics and Table II provides the output of the full 2 × 2 × 2 × 3 repeated measures ANOVA. Significant main effects show that global loudness change was significantly greater in response to: vowel (M = 64.76, SE = 1.83) relative to white-noise conditions (M = 61.49, SE = 1.95); up-ramps (M = 71.28, SE = 1.80) relative to down-ramps (M = 54.96, SE = 2.19); and high region (M = 68.76, SE = 1.84) relative to low region of intensity change (M = 57.49, SE = 1.93). Furthermore, global loudness change significantly increased as stimulus duration increased from 1.8 s (M = 57.98, SE = 2.13), to 3.6 s (M = 63.62, SE = 1.92), through to 7.2 s (M = 67.77, SE = 1.86) (post-hoc pairwise comparisons were significant with p-values < .01). As can also be seen from descriptive statistics in Table I and significant interactions in Table II, in most circumstances the effects of intensity direction, intensity region, and duration reported above are of a greater magnitude in response to vowel relative to white-noise conditions.

3.1. Vowel conditions

First, it was hypothesized that vowel up-ramps are perceived to change more in loudness than vowel down-ramps in both the low region (45–65 dB SPL) and high region (65–85 dB SPL) of intensity change. This hypothesis was supported. To begin, there was a significant main effect of intensity direction, $F(1, 33) = 123.57$, $p < .001$, $\eta_p^2 = .79$. Mean global loudness change in response to vowel up-ramps (M = 76.25, SE = 1.82) was significantly greater than vowel down-ramps (M = 53.27, SE = 2.36). Furthermore, a significant intensity direction × intensity region interaction was observed, $F(1, 33) = 93.15$, $p < .001$, $\eta_p^2 = .74$. As can be seen in the top-left panel of Figure 1, global loudness change in response to up-ramps significantly increased as intensity region and thus up-ramp end-level increased, while no such effect was observed for down-ramps. As a result, mean global loudness change in response to low and high region up-ramps was significantly greater than low and high region down-ramps, respectively. Second, it was hypothesized that vowel up-ramps are perceived to change more in loudness than vowel down-ramps across all stimulus durations. This hypothesis was supported. A significant intensity direction × duration interaction was observed, $F(1.54, 50.83) = 23.04$, $p < .001$, $\eta_p^2 = .41$, $\varepsilon = .77$. As illustrated in the middle-left panel of Figure 1, global loudness change in response to vowel up-ramps but not down-ramps increased as stimulus duration increased. This up-ramp-specific effect of duration resulted in greater global loudness change in response to vowel up-ramps relative to vowel down-ramps across all three stimulus durations (post-hoc pairwise comparisons were significant with p-values < .01). The three-way interaction between intensity direction, intensity region, and duration showed a weak yet significant result, $F(1.68, 55.46) = 3.46$, $p = .05$, $\eta_p^2 = .01$, $\varepsilon = .84$.

Finally, for replication and extension of the balanced end-level results reported in [20], it was hypothesized that 45–65 dB SPL low region vowel up-ramps are perceived to change more in loudness than 85–65 dB SPL high region vowel down-ramps within 3.6 s and 7.2 s conditions, but not 1.8 s conditions. This hypothesis was investigated by conducting a 2 × 3 repeated measures ANOVA with intensity direction (low region 45–65 dB SPL up-ramps, high-region 85–65 dB SPL down ramps) and duration (1.8 s, 3.6 s, and 7.2 s) as input parameters. This hypothesis was supported from a significant intensity direction x duration interaction, $F(2, 66) = 18.19$, $p < .001$, $\eta_p^2 = .36$. As can be seen in the bottom-left panel of Figure 1, the results of three post-hoc pairwise comparisons confirmed that global loudness change was significantly greater for

Table I. Mean Global Loudness Change in Response to Dynamic Intensity Conditions. Standard deviations shown in parentheses. A score of ‘0’ represents no perceived change in loudness and ‘100’ represents a large perceived change in loudness.

		Low Region (45–65 dB SPL)		High Region (65–85 dB SPL)	
		Up-Ramps	Down-Ramps	Up-Ramps	Down-Ramps
Vowel	1.8 s	55.49 (16.93)	56.44 (18.32)	77.43 (15.21)	49.97 (14.39)
	3.6 s	66.52 (13.63)	53.96 (15.59)	87.80 (10.63)	51.08 (15.37)
	7.2 s	77.35 (11.64)	55.27 (21.72)	92.90 (9.31)	52.90 (20.00)
White-Noise	1.8 s	47.26 (16.75)	51.46 (16.14)	70.80 (14.44)	54.96 (17.16)
	3.6 s	56.21 (17.10)	54.82 (17.23)	80.15 (13.25)	58.43 (17.89)
	7.2 s	57.07 (14.98)	57.96 (19.48)	86.40 (11.42)	62.29 (16.50)

Table II. Output for Complete 2 × 2 × 2 × 3 Repeated Measures Analysis of Variance. Spectrum = Spectrum variable (Vowel, White-Noise); Direction = Intensity Direction variable (Up-ramp, Down-ramp); Region = Intensity Region variable (High 65–85 dB, Low 45–65 dB); Duration = Duration variable (1.8 s, 3.6 s, 7.2 s). Where the assumption of sphericity was not met using Mauchly’s test of sphericity, Greenhouse-Geisser corrections to degrees of freedom were made and relevant epsilon (ε) values are reported.

Effect	*df*	F-value	p-value	η_p^2	ε-value
Spectrum	1,33	10.32	.003	.24	-
Direction	1, 33	96.72	<.001	.75	-
Region	1, 33	136.70	<.001	.81	-
Duration	2, 66	28.08	<.001	.46	.65
Spectrum × Direction	1, 33	23.83	<.001	.42	-
Spectrum × Region	1, 33	25.01	<.001	.43	-
Spectrum × Duration	2, 66	.49	.583	.01	.85
Direction × Region	1, 33	98.78	<.001	.75	-
Direction × Duration	2, 66	15.52	<.001	.32	.83
Region × Duration	2, 66	.26	.77	.01	-
Spectrum × Direction × Region	1, 33	.59	.448	.02	-
Spectrum × Direction × Duration	2, 66	10.41	<.001	.24	-
Spectrum × Region × Duration	2, 66	3.40	.039	.09	-
Direction × Region × Duration	2, 66	.40	.674	.01	-
Spectrum × Direction × Region × Duration	2, 66	5.15	.008	.13	-

45–65 dB SPL up-ramps relative to 85–65 dB SPL down-ramps at stimulus durations of 3.6 s and 7.2 s (p-values $< .001$). However, as predicted, there was no significant difference in global loudness change between 1.8 s up-ramps and down-ramps when their end-levels were equivalent ($p > .05$).

3.2. White-noise conditions

The 2 × 2 × 3 repeated measures ANOVA conducted for vowel conditions was also conducted for white-noise conditions. In accordance to previous results investigating global loudness change in response to white-noise stimuli [10], no differences between white-noise up-ramps and down-ramps were predicted across all regions of intensity change and stimulus durations. This hypothesis was not supported. First, a significant main effect of intensity was observed, $F(1, 33) = 18.84$, $p < .001$, $\eta_p^2 = .36$, indicating that mean global loudness change in response to white-noise up-ramps (M = 66.32, SE = 2.11) was significantly greater than white-noise down-ramps (M = 56.65, SE = 2.37). A significant intensity direction × intensity region interaction further elucidates this result, $F(1, 33) = 68.51$, $p < .001$, $\eta_p^2 = .68$. As can be seen in the top-right panel of Figure 1, global loudness change in response to white-noise up-ramps was greater than white-noise down-ramps in the high region of intensity change, but not in the low region of intensity change. This result provides evidence that the significant main effect of intensity direction is primarily driven by differences in the high intensity region. Furthermore, a significant intensity direction x duration interaction was observed, $F(2, 66) = 3.70$, $p < .05$, $\eta_p^2 = .10$. Similar to the vowel conditions (but smaller in magnitude), the middle-right panel of Figure 1 shows that global loudness change in response to white-noise up-ramps increased as stimulus duration increased, leading to greater global loudness change in response to white-noise up-ramps relative to down-ramps across all stimulus durations (post-hoc pairwise comparisons were significant with p-values $< .05$). There was no significant three-way interaction between intensity direction, intensity region, and duration, $F(2, 66) = .92$, $p > .05$, $\eta_p^2 = .03$.

Finally, it was hypothesized that under balanced end-level conditions, no significant differences between white-noise up-ramps and down-ramps should be observed. As with the vowel balanced end-level analysis, this hypothesis was investigated by conducting a 2 × 3 repeated measures ANOVA with intensity direction (low region 45–65 dB

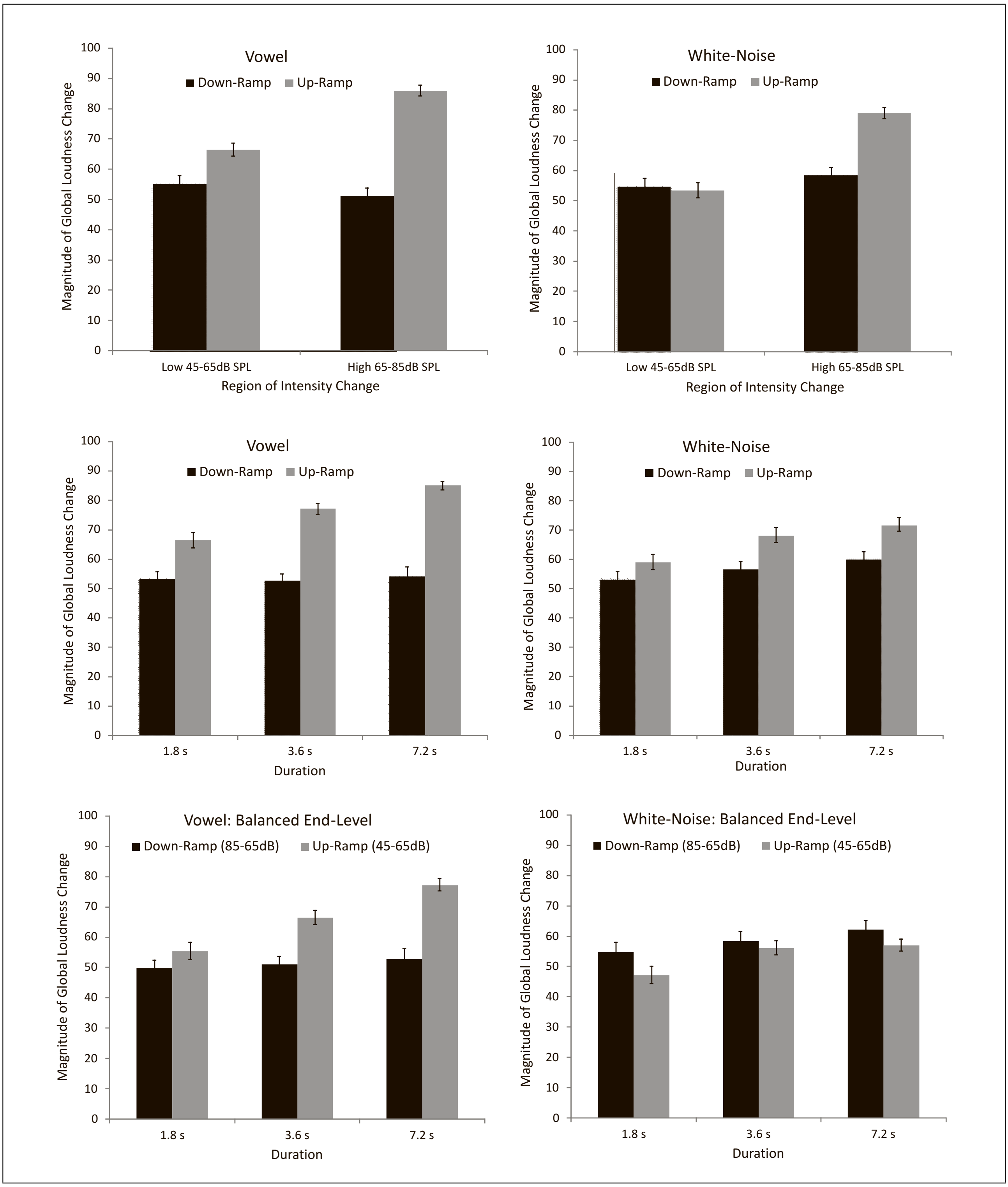

Figure 1. Mean global loudness change results for up-ramps and down-ramps of intensity. The left column of panels report vowel conditions and the right column of panels report white-noise conditions as a function of intensity region (top row) and ramp duration (middle row). The bottom row reports the balanced end-level analyses comparing 45–65 dB SPL up-ramps with 85–65 dB SPL down-ramps. On the y-axis, ‘0’ represents no change in loudness and ‘100’ represents a large change in loudness. Error bars represent standard error of the mean.

SPL up-ramps, high-region 85–65 dB SPL down ramps) and duration (1.8 s, 3.6 s, and 7.2 s) as input parameters. The hypothesis was not supported from a weak yet significant main effect of intensity direction, $F(1, 33) = 4.22$, $p = .05$, $\eta_p^2 = .11$. The intensity direction × duration interaction was not significant, $F(2, 66) = 1.39$, $p > .05$, $\eta_p^2 = .04$. As shown in the bottom-right panel of Figure 1, global loudness change was significantly greater for white-noise down-ramps relative to white-noise up-ramps under balanced end-level conditions, a result that did not vary as a function of duration.

3.3. Steady-state control conditions

Although the main aim of the present study was to investigate differences in global loudness change in response to dynamic intensity stimuli, steady-state conditions were also presented as a type of control to evaluate the characteristics of global loudness change when no physical acoustic intensity change was presented. As can been seen in Figure 2, participants perceived global loudness change in response to all steady-state stimuli, even though these stimuli did not change in intensity. To investigate these steady-state results further, a 2 × 3 × 3 repeated measures ANOVA was conducted including spectrum (vowel, white-noise), intensity (45, 65, 85 dB SPL), and duration (1.8 s, 3.6 s, 7.2 s).

Results from the repeated measures ANOVA show a significant main effect of spectrum, $F(1, 33) = 67.93$, $p < .001$, $\eta_p^2 = .67$, indicating that global loudness change in response to steady-state stimuli was significantly greater for vowel conditions (M = 21.86, SE = 1.98) relative to white-noise (M = 7.50, SE = 1.15). Second, there was a significant main effect of intensity, $F(1.66, 54.72) = 51.09$, $p < .001$, $\eta_p^2 = .61$, $\varepsilon = .83$, indicating that global loudness change increased as the magnitude of steady-state intensity increased from 45 dB SPL (M = 6.38, SE = 1.08), to 65 dB SPL (M = 12.56, SE = 1.53), through to 85 dB SPL (M = 25.09, SE = 2.38). Third, there was a significant main effect of duration, $F(1.39, 45.72) = 73.25$, $p < .001$, $\eta_p^2 = .69$, $\varepsilon = .69$, showing that the magnitude of global loudness change significantly increased as stimulus duration increased from 1.8 s (M = 7.90, SE = 0.94), to 3.6 s (M = 15.58, SE = 1.42), through to 7.2 s (M = 20.55, SE = 1.95) (all post-hoc pairwise comparisons for intensity and duration main effects were significant with p-values < .001).

As illustrated in Figure 2, significant interactions were also observed. First, it is evident from a significant spectrum × intensity interaction that the effect of steady-state intensity reported above is significantly greater for vowel relative to white-noise conditions, $F(1, 33) = 50.40$, $p < .001$, $\eta_p^2 = .60$. Similarly, the effect of steady-state duration reported above is greater for vowel relative to white-noise conditions, as shown from a significant spectrum × duration interaction, $F(1.70, 55.97) = 31.54$, $p < .001$, $\eta_p^2 = .49$, $\varepsilon = .85$. Finally, a significant intensity × duration interaction indicates that the effect of steady-state duration on global loudness change increased in magnitude as the intensity of each steady-state stimulus increased from 45 dB SPL through to 85 dB SPL, $F(2.77, 91.27) = 22.50$, $p < .001$, $\eta_p^2 = .41$, $\varepsilon = .69$, a result that was again greater for vowel relative to white-noise conditions. This observation is supported by a significant three-way spectrum × intensity × duration interaction, $F(3.02, 99.59) = 9.78$, $p < .001$, $\eta_p^2 = .23$, $\varepsilon = .75$.

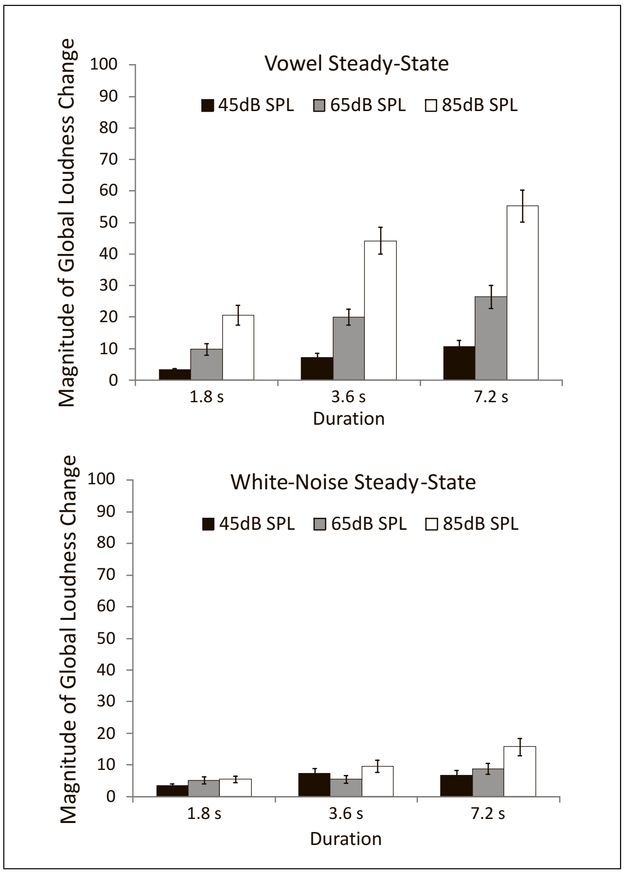

Figure 2. Mean global loudness change in response to vowel and white-noise steady-state conditions. Stimuli were presented at three steady-state levels (45, 65, 85 dB SPL) and three durations (1.8 s, 3.6 s, 7.2 s). On the y-axis, '0' represents no change in loudness and '100' represents a large change in loudness. Error bars represent standard error of the mean.

4. Discussion

In the context of continuous up-ramps and down-ramps of acoustic intensity, the present study aimed to investigate end-level recency and up-ramp-specific effects of duration on global loudness change. Overall, the results support previous studies showing that a retrospective judgment of global loudness change is strongly weighted on up-ramp end-level perception [6, 19, 20, 21, 22, 23]. As can be seen in Figure 1, global loudness change in response to up-ramps increased as a function of intensity region and end-level, with stronger effects for vowel relative to white-noise conditions. Specifically, as the end-level of up-ramps increased, so did global ratings of loudness change, even though the magnitude of intensity change was identical within each ramp's region of intensity change (20 dB). The effects of up-ramp intensity region and end-level reported here are similar to those reported in Susini *et al.* [23] in the context of global loudness (i.e., an overall impression of loudness, rather than loudness change). In the Susini *et al.* study, one group of participants were asked to assign a number (a magnitude estimation) to their global loudness impression of 1.8 s, 1 kHz pure tone up-ramps that changed over ranges of 15 dB and 30 dB. A strong effect of up-ramp region and end-level was reported. Specifically, global loudness significantly increased in magnitude as the region of each up-ramp increased from 45–60 dB SPL to 75–90 dB SPL for 15 dB ranges, and 45–75 dB SPL to 60–90 dB SPL for 30 dB ranges. This result is not surprising, as a global loudness impression in response to an up-ramp is expected to increase as the ramp's average intensity, region of change, and end-level increases [6, 23, 31]. However, when a separate group of participants rated global loudness change, very similar results were observed to the group that rated global loudness. Therefore, it may be that perception of global loudness change is influenced by the global loudness impression of an up-ramp's average intensity, despite the fact that participants are given specific instructions to focus only on the magnitude of global loudness change between ramp onset and offset, rather than overall loudness (see also [17]). This explanation can help interpret the present study's intensity-region effects in the context of up-ramp global loudness change, but cannot explain why the magnitude of global loudness change in response to down-ramps was not as affected by a 'global loudness' impression of each region of intensity change.

Results from the manipulation of ramp duration showed that overall, global loudness change was significantly greater in response to 1.8 s, 3.6 s, and 7.2 s vowel up-ramps relative to 1.8 s, 3.6 s, and 7.2 s vowel down-ramps. This provides support for the study's second hypothesis and replicates the findings of Neuhoff [10] and Olsen *et al.* [20] with 1.8 s vowel conditions and 3.6 s vowel conditions, respectively. Results from the longer 7.2 s conditions extended previous findings and confirm that the magnitude of perceived difference in global loudness change between vowel up-ramps and down-ramps increased with stimulus duration. For white-noise conditions, an equivalent effect of duration was evident, but to a lesser degree than vowel conditions. These effects of duration on global loudness change are again similar to data previously reported in the context of global loudness in response to pure tone up-ramps presented at durations between 2 s and 20 s [21].

4.1. Balanced end-level analyses

One of the primary aims of the present study was to investigate the influence of stimulus duration on global loudness change under conditions where up-ramp and down-ramp end-levels were balanced. A balanced end-level analysis controls the aforementioned effects of end-level recency associated with retrospective global judgements of loudness change [2, 20], and is realized in the present study by comparing responses to 45–65 dB SPL up-ramps with 85–65 dB SPL down-ramps. Under balanced end-level conditions and with end-level recency controlled, global loudness change was significantly greater in response to 45–65 dB SPL up-ramps relative to 85–65 dB SPL down-ramps in 3.6 s and 7.2 s vowel conditions only. This was facilitated by an up-ramp-specific effect of duration, where the magnitude of global loudness change increased as vowel up-ramp duration increased from 3.6 s to 7.2 s. Consequently, the 'balanced end-level' result for vowel conditions replicates and extends the balanced end-level results originally reported in Olsen, *et al.* [20] and shows a clear up-ramp-specific effect of duration on global loudness change that cannot be explained by cognitive constraints such as recency in memory. White-noise conditions did not elicit this effect. Rather, global loudness change was significantly greater for 85–65 dB SPL white-noise down-ramps relative to 45–65 dB SPL white-noise up-ramps across all stimulus durations, a result opposite to those observed from the vowel balanced end-level analyses.

The original 'bias for rising intensity' hypothesis [10] predicts differences between vowel and white-noise conditions such as those reported above. However, the original experiments that led to this prediction did not control for retrospective response biases such as end-level recency [10, 12]. The design of the present study controlled end-level recency through the use of balanced end-level analyses and provided evidence that tonal up-ramps are indeed perceived to change significantly more in global loudness than tonal down-ramps, whereas for white-noise these differences are eliminated. However, this result is only applicable for stimulus durations beyond the 1.8 s conditions originally used in Neuhoff's experiments [10, 12]. Indeed, the 'bias for rising intensity' hypothesis in [10] does not account for the up-ramp-specific effects of duration reported here when end-level recency is controlled, a result that we will now discuss in more detail.

4.2. Acoustic 'tau', time-to-contact, and an up-ramp-specific effect of duration

Why is it that in the present study we observe such a large increase in global loudness change as up-ramp duration increases? The concept of an acoustic 'Tau' effect and auditory time-to-contact research may be applicable here. The original 'Tau' effect reported in Helson [32] describes illusions of spatial perception due to temporal variations in stimulus presentation. For example, if three lights equally spaced along an invisible line flash one after another, the distance between the second and third light is perceived to be greater as more time passes between each flash [33]. The Helson [32] 'Tau' effect can also be induced in the auditory domain. For example, as a sound-emitting object's speed of movement gets faster, the shorter the distance the sound source is perceived to have traveled [34]. On the other hand, the slower the movement, the greater the perceived distance travelled. In the context of the present set of stimuli, if perceived distance of implied motion from up-ramps and down-ramps is affected by stimulus duration, this version of a 'Tau' effect would predict that longer sounds are likely to be perceived to cover a greater implied distance. Furthermore, global judgements of loudness change are associated with a proximity estimate and thus a spatial assessment used for judgements of sound source distance and motion [10, 12, 27, 28]. Therefore, this version of a 'Tau' effect may also explain why the magnitude of perceived loudness change increases with stimulus duration. However, this alone does not explain why the effects of duration reported in the present study are greater for up-ramps relative to down ramps.

Studies of perceived sound source time-to-contact [35] may offer further insight. In time-to-contact studies, a looming sound source is often perceived to arrive at a point in space sooner than would be expected from the physical velocity of the approaching stimulus [15, 16]. This underestimation of a stimulus' time-to-contact is related to the finding that in free-field listening conditions, a looming sound source is perceived to stop closer to the listener and travel a greater perceived distance than a receding sound source presented with an equivalent distance, duration, and stopping point [12]. Furthermore, in the visual domain, the tendency towards underestimating the time-to-contact of a looming stimulus has been shown to increase when the velocity of a looming stimulus is presented at a slow rate of change, relative to a fast rate of change [36, 37]. In auditory time-to-contact experiments, one way of manipulating the velocity of a looming sound source is to vary the duration of approach over a fixed distance. In this example, the rate of change per unit time will be slower as the duration of the approaching stimulus is lengthened. In loudness change experiments, a similar manipulation may vary the duration of an up-ramp over a fixed intensity range (in the present study, 20 dB). Here, the rate of change per unit time within the up-ramp decreases as the duration of its presentation increases. In this context, the aforementioned effect of velocity on underestimating time-to-contact of a looming stimulus is analogous to the up-ramp-specific effects of duration reported herein, where longer durations of up-ramp stimuli contain slower rates of intensity change, yet are perceived to change significantly more in loudness than stimuli with shorter durations and thus faster rates of intensity change. It is again important to note here that in all cases, the actual physical magnitude of intensity change was identical between up-ramps and down-ramps.

However, this explanation also has its limitations. If one takes the durations (1.8 s, 3.6 s, and 7.2 s) and intensity range (20 dB) of up-ramps used in the present study and assumes a constant-velocity approach, the time-to-contact after stimulus presentation is below 1000 ms when calculated using the algorithm presented in [38]; a relatively small time to 'err on the side of caution'. Furthermore, there is evidence that within these stimulus parameters, listeners typically overestimate rather than underestimate time-to-contact [39]. However, the linear change in level used in the present study indicates a decelerating approaching object in the environment, rather than a constant-velocity approach. Therefore, actual perceived time-to-contact in response to the current set of stimuli is not entirely clear, although some evidence does suggest that linear and accelerated rates of change are not well discriminated [40]. Future work is required to understand the relationship between perceived changes in loudness and judgements of time-to-contact using stimuli that represent accelerating, decelerating, and constant-velocity looming sound sources.

4.3. Global loudness change in response to steady-state stimuli

The results from the steady-state conditions (Figure 2) show that global loudness change is observed when stimuli did not contain the usual changes of acoustic intensity necessary to affect changes in loudness. Furthermore, the magnitude of global loudness change in response to steady-state stimuli increased as intensity and stimulus duration increased. In the context of ecological acoustics, a relatively high intensity steady-state sound may be perceived closer in space to the listener and thus represent a more 'salient' stimulus than a less intense sound. The perceived salience of a sound's high-intensity could further elicit an illusory perception of change if perceived to move over a greater implied distance (analogous here to the increase of stimulus duration from 1.8 s, 3.6 s, through to 7.2 s). Therefore, such an illusory 'change' response may simply be due to the stimulus containing acoustic and temporal information that is of high relevance to the listener.

Indeed, it is likely that factors such as stimulus duration provided additional salient cues for judgements of global loudness change when no physical change of intensity was present. For example, if participants either consciously or nonconsciously based their global 'change' response on stimulus duration, then it would not be surprising to observe greater perceived change in response to longer duration stimuli relative to those with shorter durations. Furthermore, a steady-state stimulus with high intensity elicits high ratings of global loudness [41]. This fundamental intensity/loudness relationship may interact with stimulus duration and result in global loudness change responses that increase in magnitude as overall intensity and duration increases. Such an effect would lead to the results reported in Figure 2.

It is clear that a more complete understanding of the mechanisms underlying these surprising yet intriguing steady-state results awaits further clarification. Nevertheless, the findings of the present study provide strong evidence that the illusory perception of change in response to steady-state stimuli is affected by the spectrum, duration, and intensity of the stimulus. Moreover, the magnitude of these effects is facilitated by each of these individual factors.

5. Conclusion and future directions

The findings of the present study replicated and extended previous research showing that retrospective ratings of global loudness change are strongly weighted on up-ramp end-level intensity [6, 20, 23]. This result provides further evidence of an end-level recency effect when global loudness change is measured. When end-level recency *was not* controlled, vowel (/ə/) and white-noise up-ramps were perceived to change significantly more in global loudness than their corresponding down-ramps; a result that increased in magnitude with stimulus duration and region of intensity change. In almost all cases, these effects were greater in response to vowel relative to white-noise conditions. When end-level recency was controlled through the use of a balanced end-level analysis, global loudness change was significantly greater for up-ramps relative to down-ramps in 3.6 s and 7.2 s vowel conditions only. Furthermore, an up-ramp-specific effect of duration was observed for vowel conditions in the balanced end-level analysis: the magnitude of global loudness change increased as the duration of up-ramps but not down-ramps increased from 3.6 s to 7.2 s. When these results are considered in the broader context of ecological acoustics and in particular, perceived distance and implied motion, acoustic 'Tau' and time-to-contact phenomena offer novel perspectives in which to interpret the up-ramp-specific effects of duration observed here in the context of global loudness change.

Future studies investigating up-ramp 'perceptual salience' will benefit from novel directions that move beyond psychoacoustic investigations of loudness; for example, dynamic acoustic intensity perception in the context of auditory attentional capture and spatial hearing. In the visual domain, implied looming stimuli capture attention (e.g., an expanding two-dimensional stimulus resulting in an expanding pattern on the retina), whereas receding stimuli do not [42, 43] (but see [44]). In the auditory domain, implied looming from up-ramps of intensity embedded within short artificial, musical, and environmental sounds elicit high ratings of arousal and negative valence (i.e., unpleasantness) [11, 45, 46] – two key elements of negative affect that are important for orienting auditory spatial attention [47, 48, 49, 50]. It is likely that auditory spatial attention is a key mechanism underlying perception of salient acoustic features associated with real and implied looming auditory motion. Investigating auditory spatial attention in the context of fast and accurate localization of dynamic sound sources is a promising future direction that will shed greater light on psychological mechanisms underlying any 'perceptual priority' [10] demanded by up-ramps in an ecologically valid spatial hearing context.

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