INTENSITY DYNAMICS AND LOUDNESS CHANGE: A REVIEW OF METHODS AND PERCEPTUAL PROCESSES

Kirk N. Olsen
The MARCS Institute, University of Western Sydney, Australia
k.olsen@uws.edu.au

In real-world listening domains such as speech and music, acoustic intensity and perceived loudness are dynamic and continuously changing through time. The percept of loudness *change* in response to continuous increases (up-ramps) and decreases (down-ramps) of intensity has received ongoing empirical and theoretical interest, the result of which has led to conflicting findings from a range of key paradigms. Therefore, the aim of this brief review is to: (a) describe key paradigms used to measure changes in loudness in response to continuous intensity change; (b) identify methodological issues associated with each paradigm; and (c) discuss the mechanisms proposed to explain differences in loudness change when methodological constraints and response biases are controlled. It is concluded that direct and indirect measures of loudness change reflect two distinct aspects of auditory perception. Specifically, magnitude estimation and continuous loudness paradigms reflect changes in perception associated with a ramp's direction and magnitude of intensity change, and empirical evidence supports the conclusion that greater loudness change in response to down-ramps relative to up-ramps is the real-time perceptual outcome. On the other hand, retrospective global judgements of loudness change are disproportionally weighted on end-level intensity rather than magnitude of intensity change. However, an up-ramp-specific effect of duration on global loudness change is evident when end-level response bias is controlled, and this may be associated with end-point time-of-arrival responses to real and apparent looming auditory motion.

INTRODUCTION

The association between acoustic signals and their perception is a fundamental issue in auditory psychophysics. In psychological terms, the subjective percept of loudness is closely related to a sound's physical intensity and is broadly defined as the magnitude of auditory sensation [1, 2]. However, the relationship between acoustic intensity and loudness is not straightforward. Additional acoustic parameters such as frequency play a significant role in loudness perception, as evident by frequency-dependent equal-loudness contours [3, 4]. Mapping loudness across the frequency spectrum has been made possible by the use of psychoacoustic steady-state stimuli. These are stimuli with intensity profiles that do not vary through time and thus offer the experimenter a high degree of stimulus control. However, almost all real-world sounds are dynamic, with continuous changes in acoustic and perceptual parameters such as increases and decreases of intensity and loudness.

For the purpose of the present paper, a continuous rise of intensity is defined as an 'up-ramp'; a ramp of intensity (in experiments, most often linear) that continuously rises from relatively low intensity to relatively high intensity. Conversely, a continuous decrease of intensity is defined as a 'down-ramp'. Paradigms measuring *changes* in loudness both directly and indirectly have been used to investigate the mechanisms underlying the perception of time-varying, temporally dynamic intensity stimuli. This is an important line of research in auditory psychophysics, as intensity and loudness are dynamic aspects of real-world listening in domains such as speech and music. Furthermore, fundamental psychophysical research on dynamic intensity and loudness change has far-reaching implications for and applications to fields such as ecological psychoacoustics, music perception, composition, and performance, sound engineering, and the design of informative auditory warnings [5-9]. However, paradigms used to investigate changes of intensity and loudness have led to a range of conflicting results; results that can begin to be reconciled with a systematic analysis of methodological similarities, differences, benefits, and shortcomings.

Therefore, the overarching aim of the present paper is to organise and briefly review research investigating the dynamic percept of loudness change in response to continuous acoustic intensity change. Specifically, the paper will: (a) describe the key paradigms used to measure changes in loudness in response to continuous intensity change; (b) identify methodological benefits and shortcomings associated with each paradigm; and (c) discuss the mechanisms proposed to explain differences in loudness change when methodological constraints and response biases are controlled.

DOWN-RAMP DECRUITMENT AND LOUDNESS MAGNITUDE ESTIMATION

Early studies investigating changes in loudness as a function of continuous increases and decreases of intensity used traditional psychophysical measurements such as magnitude estimation [10]. Developed from the seminal work of S. S. Stevens [11], magnitude estimates of loudness in the current context require listeners to make discrete numerical estimations of loudness in response to the intensity at stimulus onset, offset, and sometimes intermittently throughout each dynamic intensity sweep. In its simplest form, loudness change is 'indirectly' calculated as the ratio between the two discrete onset and offset loudness estimates. For pure-tone up-ramp and down-ramp stimuli presented at durations from ~10 s to 180 s, the ratio of loudness change for a down-ramp is greater than a corresponding up-ramp stimulus matched on parameters such as frequency, duration, range, and region of intensity change [10, 12-15]. The greater magnitude of loudness change in response to down-ramp tonal stimuli has been termed 'decruitment'. As can be seen in Figure 1, decruitment is due to the observation that loudness falls more rapidly as the continuous 65-20dB sound pressure level (SPL) decrease of intensity falls below ~40dB SPL [10]. This, in turn, leads to the relatively low 20dB SPL end-level (offset) of the down-ramp to be perceived as 'softer' in loudness than the equivalent 20dB SPL onset of the 20-65dB SPL up-ramp. The reciprocal phenomenon of 'upcruitment' does not elicit such pronounced effects on up-ramp perception, resulting in a smaller ratio of loudness magnitude estimates between up-ramp onset and offset levels. Furthermore, when intermittent tones are presented with decreasing levels, decruitment is not observed [10]. These data show that the specific direction and continuity of intensity change over time are significant factors for down-ramp decruitment.

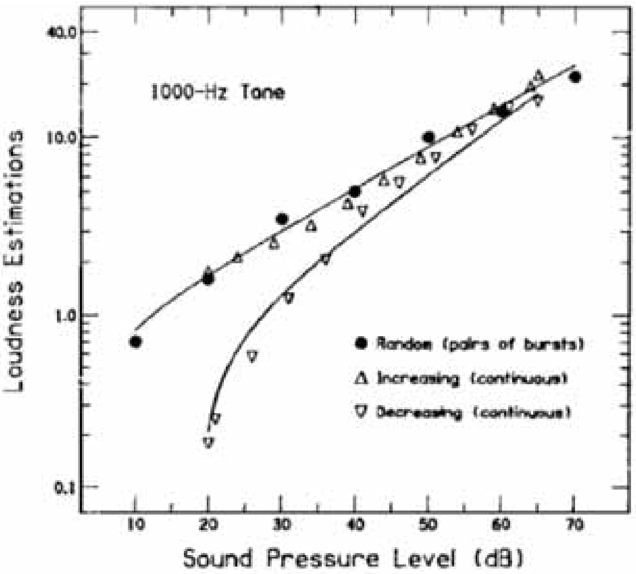

Figure 1. Geometric mean loudness magnitude estimates of a 180 s 1kHz pure tone plotted as a function of level for three modes of signal presentation: upward triangles represent responses to a continuously increasing (up-ramp) tone from 20-65dB SPL; downward triangles represent responses to a continuously decreasing (down-ramp) tone from 65-20dB SPL; and circles represent responses to pairs of intermittent tones presented at seven levels in random order [10]. The loudness curve rapidly steepens as the down-ramp continuously decreases below 40dB SPL, whereas the loudness curve in response to the up-ramp increases linearly on a log scale across the entire range of intensity change. (Reprinted with permission from [10]. Copyright 1990, Acoustical Society of America).

The candidate mechanism underlying down-ramp decruitment is still not completely understood. However, sensory adaptation has been proposed [10, 14, 16]. If the early and relatively high intensity portions of the down-ramp were to adapt neurons responsible for coding the sound, the latter portions of the down-ramp would become less audible. By contrast, the early and relatively low intensity portions of the up-ramp may not cause substantial adaptation for latter, higher-intensity portions. In this scenario, the offset of the down-ramp is likely to be perceived 'softer' than the equivalent intensity onset of the up-ramp. Indeed, this is the case in observations of decruitment. It is unlikely, however, that a sensory mechanism such as adaptation can completely explain down-ramp decruitment [12]. The relative influence of cognition has been investigated using a dual-task paradigm, with results suggesting that the magnitude of decruitment depends on whether listeners actively attend to the stimulus [14]. Computational models that can account for decruitment do not currently exist, and ongoing work aims to develop a model that explains behavioural data and the cognitive and sensory mechanisms underlying this phenomenon.

GLOBAL LOUDNESS CHANGE AND A 'PERCEPTUAL BIAS' FOR RISING INTENSITY

One potential shortcoming associated with measures of loudness change from discrete magnitude judgments is that perceived change is not measured directly. Rather, it is inferred from differences in static loudness responses that reflect *overall* loudness at specific points in time [17]. One alternative to measuring static judgements of loudness across stimulus presentation is to ask listeners to directly judge the magnitude of loudness change after stimulus presentation. A retrospective discrete post-stimulus judgement of perceived change in loudness is termed 'global loudness change'. Neuhoff [18] used this method to investigate loudness change in response to 1.8 s up-ramps and down-ramps presented as 1kHz pure-tone, white-noise, or vowel stimuli (/ə/ - sounds like the 'a' in 'about'). The range of each ramp was 15dB and participants made a global judgement of loudness change in response to single-ramp trials (a single-stimulus paradigm) using a computer-based visual analogue scale. From this post-stimulus response, pure-tone and vowel up-ramps were perceived to change significantly more in loudness than down-ramps; a finding opposite to those of decruitment studies. No significant differences were observed for white noise. These results have now been replicated and extended using 3.6 s vowel stimuli in a comparable single-stimulus paradigm [19], as well as a paired-stimulus paradigm where pairs of 1.8 s 30dB up-ramps and down-ramps were presented in each trial [19, 20]. In a paired-stimulus paradigm, participants are required to (a) indicate which item in a pair changed more in loudness; and (b) rate the magnitude of this difference when one was perceived.

Greater perceived loudness change for pure-tone and vowel up-ramps in this paradigm has been hypothesised as evidence of an evolved, adaptive perceptual bias to looming auditory motion in the environment [18, 20]. Continuous increases of acoustic intensity are a vital cue for looming (or approaching) auditory motion [21]. An overestimation of loudness change for up-ramp 'looming' stimuli may function as a survival response that provides a selective advantage for organisms able to underestimate the arrival of a looming object, effectively allowing extra time to 'err on the side of caution' when taking appropriate action (e.g., avoidance or retreat) [18, 20, 22]. Specific neural processes have been identified for auditory looming in the human brain [23-25], and evidence suggests that the hypothesized adaptive bias from judgements of global loudness change is influenced by sex differences [26]. Perceived time-to-contact and time-of-arrival studies in auditory and visual domains support the notion that real and apparent looming motion is perceived to arrive at a point in space significantly sooner than actual source arrival [27, 28]. The observation in [18] that white noise up-ramps and down-ramps are perceived similarly is explained by first assuming that white noise commonly represents multiple sound sources in the environment (e.g., ocean, rain, wind through trees) [18, 20]. According to Neuhoff, multiple sound sources should not necessarily demand equivalent behavioural priority when compared to simple (pure-tone) and complex (vowel) tonal stimuli, which are arguably more closely associated with a single sound source. However, the suggestion that looming and potentially threatening single sound sources in the environment are characterised by spectral properties akin to a pure-tone or vowel stimulus is yet to be completely substantiated.

Indeed, the 'perceptual bias for rising intensities' hypothesis and the use of global loudness change as a sensitive perceptual measure of real-time changes of intensity have been challenged [e.g., 15, 29, 30, 31]. For example, the continuous increase of intensity change that characterizes up-ramps and auditory looming is not absolutely necessary to elicit differences in global loudness change predicted by the 'perceptual bias' hypothesis [30, 32]. Furthermore, the global loudness change measure relies on retrospective post-stimulus judgements and is therefore susceptible to cognitive-based response biases that will now be addressed.

End-level bias and recency in memory

Empirical evidence shows that direct ratings of global loudness change are influenced by a 'bias for end level' [15, 19, 31]. For example, as up-ramp end-level increases in dB, so does the magnitude of global loudness change, even when the magnitude of intensity change in up-ramps is held constant [15]. Specifically, with every 15dB increase in end-level from an up-ramp with a fixed magnitude of intensity change, perceived loudness change approximately doubles. This is evidence that post-stimulus retrospective global judgements of loudness change are weighted towards the most recent portion of the up-ramp – the end-level – and not the entire magnitude of intensity change. Susini et al. [33, 34] explain an end-level bias with reference to memory-based recency. Simply, recency is defined as a memory recall bias for the last item presented in a sequence of stimuli [35]. In the context of global loudness change, the most recent portion of an up-ramp or down-ramp is its final intensity level. Recency may bias judgements of global loudness change toward the final level of intensity (end-level) of an up-ramp or down-ramp. Take the case where global loudness change in response to a 60-80dB SPL up-ramp is compared with an 80-60dB SPL down-ramp. If a cognitive-based recency mechanism were to impact this response, it is not surprising that perceived change is greater for up-ramps because, in the example above, the up-ramp ends on a level 20dB greater than that of the down-ramp. This can be described as an end-level recency mechanism in global judgements of loudness change.

To investigate the hypothesis of an end-level recency mechanism, Olsen et al. [19] balanced end-level differences in an analysis comparing 50-70dB SPL up-ramps with 90-70dB SPL down-ramps using Neuhoff's [18] /ə/ vowel stimulus at 1.8 s and 3.6 s ramp durations. In this comparison, up-ramps and down-ramps have an equivalent intensity of 70dB SPL at the end of the ramp (in other words, equivalent or 'balanced' end-levels). Participants were presented with a single-stimulus paradigm and were required to judge global loudness change retrospectively using a visual analogue scale. Results from this analysis do not provide evidence of down-ramp decruitment, and when end-level differences between 1.8 s up-ramps and down-ramps are removed, the original Neuhoffian [18] 'bias for rising intensities' is not recovered. This suggests that an end-level recency mechanism can explain the greater magnitude of global loudness change in response to 1.8 s up-ramps when end-level intensity differs between up-ramps and down-ramps [e.g., 18]. However, at the 3.6 s duration, global loudness change was significantly greater for up-ramps relative to down-ramps, even when end-level recency was controlled in the balanced end-level analysis. These data provide evidence of an up-ramp-specific effect of duration under balanced end-level conditions: global loudness change increases as a function of duration for up-ramps only, while down-ramp global loudness change is not affected by stimulus duration.

An earlier experiment using direct and unconstrained magnitude estimations of global loudness change has also investigated up-ramps and down-ramps with balanced end-levels [15]. When such a measure of global loudness change replaces the visual analogue scale used in [19], greater perceived changes in loudness in response to up-ramps were not observed for 1.8 s 1kHz pure-tone stimuli. In fact, loudness change was numerically greater in response to 1.8 s down-ramps, and this difference increased as the sweep size of each ramp doubled from 15dB to 30dB (no inferential statistics were conducted on these specific comparisons [15]).

Reasons for the somewhat varied results between experiments that controlled up-ramp and down-ramp end-level differences are not clear. Differences in scaling methods may be a factor: the experiment in [15] used an unconstrained magnitude estimation procedure to measure global loudness change, whereas the predefined visual analogue loudness scale used in [19] constrains listeners' responses. Future research directly comparing these two procedures with a design comprising multiple regions and ranges of intensity change (cf. [15]) will shed further light on how global judgements of loudness change relate to the sweep size and end-level of up-ramps and down-ramps.

Post-stimulus sensory persistence of excitation

Post-stimulus persistence of neural excitation is one candidate sensory mechanism proposed to explain the 'residual' differences in global loudness change when cognitive mechanisms such as recency are controlled under balanced end-level conditions [36, 37]. The rationale behind the persistence of excitation hypothesis is that the auditory system continues to respond to a sensory stimulus after it ceases to be presented. A longer post-stimulus *sensory* response of greater magnitude may result in a subjectively larger *perception* of change for that stimulus. This hypothesis was investigated using psychophysical forward masking [36], defined as "an elevation of hearing threshold for a target signal presented after another stimulus event: the masker. The difference between masked signal threshold and signal threshold in quiet is an indicator of masking magnitude, a measure of the auditory system's response to a sensory stimulus beyond its physical presence at a particular point in time" (p. 596). Greater masking magnitude from up-ramps relative to down-ramps under balanced end-level conditions would provide evidence of an underlying sensory mechanism most likely occurring at peripheral stages of auditory processing [but see, 38]. As displayed in Figure 2, results from a forward masking paradigm using 3.6 s vowel up-ramp and down-ramp maskers show that differences in mean masked thresholds between 40-60dB SPL up-ramps and 80-60dB SPL down-ramps were below 1.34dB SPL at masker-offset to signal-offset delays of 10 ms to 170 ms (the signal was a 10 ms 1.5kHz pure tone). These differences were not significant. After ~180-200 ms, masked thresholds returned to baseline thresholds in quiet. These results subsequently rule out post-stimulus persistence of excitation as an explanatory mechanism for differences in global loudness change between 3.6 s up-ramps and down-ramps with balanced end-levels.

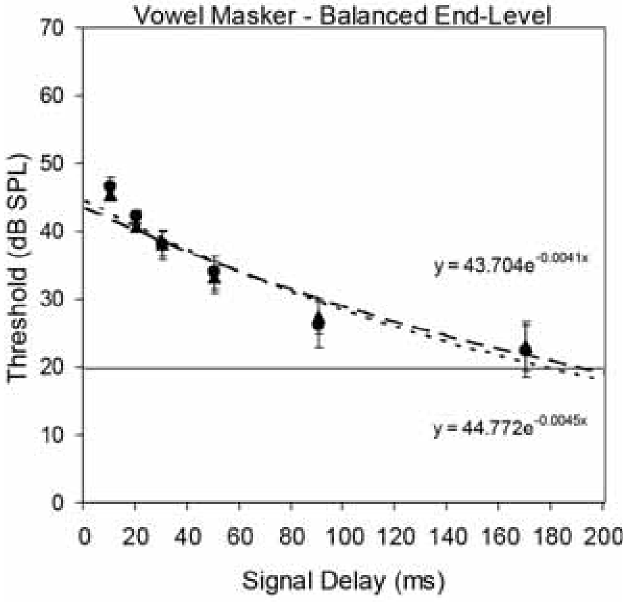

Figure 2. Mean forward-masking patterns ($N = 3$) from 3.6 s up-ramp (solid triangle) and down-ramp (solid circle) vowel maskers with masker-offset to signal-offset delays of 10, 20, 30, 50, 90, and 170 ms [36]. The signal was a 10 ms 1.5kHz pure tone. Balanced end-level comparisons (40–60dB SPL up-ramps versus 80–60dB SPL down-ramps) are displayed. Exponential curves are shown for up-ramps (dashed line, top equation) and down-ramps (dotted line, bottom equation), and error bars represent standard error of the mean. The solid horizontal line represent mean signal threshold in quiet. (Reprinted with permission from [36], Copyright 2012, Pion Ltd. www.pion.co.uk; www.envplan.com).

CONTINUOUS LOUDNESS MEASUREMENT: FURTHER EVIDENCE FOR DOWN-RAMP DECRUITMENT

An underlying similarity between direct loudness change measured from retrospective global judgements and indirect loudness change measured from static 'snapshots' of loudness magnitude is that neither are completely sensitive to changes in loudness on a continuous moment-to-moment basis. Therefore, the third key loudness change paradigm reviewed here is continuous loudness measurement. One of the benefits of a continuous measure of loudness is that end-level recency is inherently removed because a retrospective judgement of loudness change is not required. In auditory perception research, continuous responses have been used to investigate relationships between acoustic properties such as intensity, spectral flatness (a global parameter of timbre), the perception of affect (e.g., emotional arousal and valence/pleasantness), and loudness. Such studies have been undertaken in contexts ranging from traffic noise [39] to music from classical [40-42] and electroacoustic [43, 44] genres.

Only a handful of experiments, however, have systematically manipulated increases and decreases of acoustic intensity when measuring loudness continuously. Susini and colleagues [33, 34] developed an 'analogical/categorical' (A/C) scaling device for continuous loudness measurement. The response tool comprised a physical box with a slider that listeners used to continuously rate loudness on a scale containing seven categorical labels, from 'very, very loud' to 'very, very soft', with 'mid' serving as the mid-point of scale. Loudness change was calculated as the difference between loudness values recorded at the beginning and end of each ramp, analogous to magnitude estimates of loudness but in the context of continuous perceptual measurement. Using a paired-stimulus paradigm and 1kHz pure tone up-ramps (60-80dB SPL) and down-ramps (80-60dB SPL) presented at durations of 2, 5, 10, and 20 s per item, an omnibus ANOVA with N=15 did not result in a significant main effect of intensity ramp [34]. This suggests that both the 'bias for rising intensity' and decruitment effects disappear when 'indirect' loudness change is measured from a continuous response and calculated similarly to the magnitude estimates used in decruitment studies [10, 12-15].

However, in [34], sample size and statistical power was moderate at best, and no specific contrasts between up-ramps and down-ramps at each duration were analysed. From close inspection of the results of Experiment 1 in [34], loudness change was numerically greater for down-ramps relative to up-ramps across all durations. Furthermore, the mean loudness values at down-ramp offset (60dB SPL) were lower than the mean loudness values in response to the equivalent 60dB SPL up-ramp onset at stimulus durations of 5, 10, and 20 s. Taken together, these two trends in results provide some support for the main observations of decruitment: (1) that down-ramps are perceived to change more in loudness than up-ramps when calculated as the difference between ramp onset and offset loudness ratings; and (2) that greater loudness change in response to down-ramps is due to a 'softer' loudness response to down-ramp offset intensity, relative to the equivalent up-ramp onset intensity. As previously discussed, decruitment may be explained by a down-ramp adaptation mechanism, where early and relatively high intensity portions of a down-ramp adapt neurons responsible for coding the sound, resulting in latter portions of the down-ramp to become less audible. These results using continuous loudness as a tool to investigate perceptual change support this hypothesis, but here in a higher region of intensity change than those used in earlier decruitment studies [e.g., 10].

The significant role of down-ramp end-level loudness 'softening' in this decruitment-like effect has recently received further support in a musical context [45]. Using a similar continuous loudness paradigm to [34] but with a computer-based visual analogue loudness scale, 29 participants continuously rated loudness in response to a range of 6.4 s monophonic melodies constructed with up-ramp and down-ramp intensity profiles and ascending and descending melodic contours [45]. The range of each intensity sweep was either 15dB (70-85dB SPL) or 30dB (55-85dB SPL) and loudness change was calculated as the difference between loudness values at the beginning of the continuous response and the offset of each melody. Linearity of the continuous loudness responses was also investigated. Overall, musical down-ramps were perceived to change significantly more in loudness than musical up-ramps. As can been seen in Figure 3, this is explained by the significantly 'softer' loudness response to down-ramp offset intensity, relative to loudness in response to the equivalent up-ramp onset intensity. Furthermore, continuous loudness responses to down-ramps in the region between 55-85dB SPL were essentially linear. This is in contrast with the non-linearity in loudness change that characterises decruitment as down-ramps continuously decrease below 40dB SPL [10]. This difference in the loudness curve is likely due to the region of intensity change used in [45], which remained at an overall higher intensity region than decruitment studies that include levels as low as 20dB SPL.

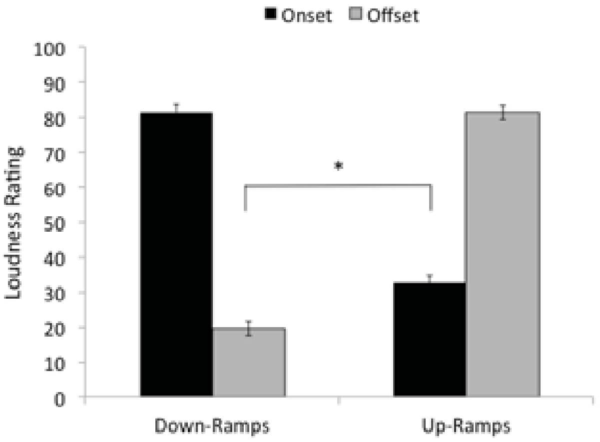

Figure 3. Mean loudness ratings at the onset of the continuous loudness response and the offset of each stimulus for 6.4 s down-ramp and up-ramp melodies presented in [45] (Experiment 1). On the y-axis, zero represents a 'soft' loudness response and 100 represents a 'loud' loudness response. No significant difference in loudness in response to the onset of the down-ramp and the offset of the up-ramp was observed. However, loudness was significantly lower in response to the offset of a down-ramp, relative to the onset of the up-ramp. Error bars report standard error of the mean; $*p < .001$. (Reprinted from [45], Copyright 2014, with permission from Elsevier).

CONCLUDING REMARKS

The present paper aimed to provide a brief review of research investigating the dynamic percept of loudness change in response to continuous acoustic intensity change. Description and evaluation of the three key paradigms used in this field of research was presented, and cognitive and sensory mechanisms that may underpin differences in perceived loudness change were discussed. It is clear from this review that conflicting results due to direct and indirect measures of loudness change reflect two distinct aspects of auditory perception.

Indirect loudness change derived from magnitude estimation and continuous loudness paradigms reflect, at the least, changes in perception associated with a ramp's direction and magnitude of intensity change. In these paradigms, loudness is measured throughout the entire dynamic stimulus; statically in the case of magnitude estimation, and continuously in the case of the continuous response. Therefore, they are the most sensitive tools for understanding real-time perception of intensity change and the mechanisms that underpin those perceptions as they unfold though time. Continued empirical evidence supports the conclusion that greater loudness change in response to down-ramps is the real-time perceptual outcome. Greater loudness change in response to down-ramps relative to up-ramps is characterised by: (1) a steeper linear loudness curve in response to down-ramps presented at intensity regions above 40dB SPL; and (2) a further rapid non-linear steepening of the loudness curve in response to down-ramps that continuously decrease below 40dB SPL. The extent to which these results are underpinned by peripheral and central mechanisms is a question that requires further behavioural evidence and computational modeling. For example, output from models of various stages of auditory processing could be used to compare with behavioural data to identify the location(s) of sensory adaptation [46-49].

Any method that purports to be a valid measure of loudness change must be supported by evidence that it is indeed sensitive to the magnitude of intensity change. It is clear from this review that global loudness change is disproportionally weighted on end-level intensity perception, rather than the magnitude of intensity change within each dynamic sweep. However, when differences between up-ramp and down-ramp end-levels are controlled in experimental design and analysis, an up-ramp-specific effect of duration remains: global loudness change in response to up-ramps increases as a function of duration, even when the range of physical intensity change remains constant and end-level recency is controlled. Neuhoff [17] argued that a direct global judgement of loudness change in response to an up-ramp looming stimulus in the environment is more useful for localizing a moving sound source than snapshot judgements of loudness at discrete points in time. The results of global loudness change reviewed here are most consistent with auditory and visual research that investigates anticipatory or predictive perceptions to real and apparent looming motion; perceptions that are usually measured after motion offset. In these studies, looming stimuli are perceived to arrive at a point in space sooner than what would be expected from the physical velocity of the approaching stimulus [27, 28].

The magnitude of underestimation for a looming stimulus' time-of-arrival increases as the velocity of a visual looming stimulus becomes slower [50, 51]. This is analogous to the up-ramp-specific effect of duration reported above, where longer durations of up-ramp 'looming' stimuli contain slower rates of intensity change over time, but elicit a greater magnitude of global loudness change than stimuli with shorter durations and faster rates of change. One may speculate, therefore, that global loudness change reflects – at least in part – the effects of duration and rate (but not magnitude) of intensity change for end-point time-of-arrival responses to real and apparent looming auditory motion.

ACKNOWLEDGEMENTS

Thanks to Robert Teghtsoonian, one anonymous reviewer, Kate Stevens, and the MARCS Institute Music Cognition and Action research group for helpful comments on an earlier draft.

REFERENCES

[1] Moore, B. C. J., *An introduction to the psychology of hearing.* 5th ed., Boston: Academic Press 2003

[2] Olsen, K. N., Loudness and intensity, in *Music in the Social and Behavioral Sciences: An Encyclopedia,* W.F. Thompson, Editor. 2014, Sage Publications: New York.654-657.

[3] Fletcher, H. and Munson, W. A., "Loudness, its definition, measurement and calculation", *Journal of the Acoustical Society of America* **5**, 82-108 (1933)

[4] Suzuki, Y. and Takeshima, H., "Equal-loudness-level contours for pure tones", *Journal of the Acoustical Society of America* **116**, 918-933 (2004)

[5] Olsen, K. N. and Stevens, C. J., "Psychophysiological response to acoustic intensity change in a musical chord.", *Journal of Psychophysiology* **27**, 16-26 (2013)

[6] Thompson, W. F., Peter, V., Olsen, K. N., and Stevens, C. J., "The effect of intensity on relative pitch", *Quarterly Journal of Experimental Psychology* **65**, 2054-2072 (2012)

[7] Dean, R. T., Olsen, K. N., and Bailes, F., "Is there a 'rise-fall temporal archetype' of intensity in the music of Joseph Haydn? The role of the performer", *Journal of Music Performance Research* **6**, 39-67 (2013)

[8] Neuhoff, J. G., *Ecological psychoacoustics*. Amsterdam: Elsevier Academic Press 2004

[9] Croghan, N. B., Arehart, K. H., and Kates, J. M., "Quality and loudness judgments for music subjected to compression limiting", *Journal of the Acoustical Society of America* **132**, 1177-1188 (2012)

[10] Canévet, G. and Scharf, B., "The loudness of sounds that increase and decrease continuously in level", *Journal of the Acoustical Society of America* **88**, 2136-2142 (1990)

[11] Stevens, S. S., "The direct estimation of sensory magnitudes: Loudness", *The American Journal of Psychology* **69**, 1-25 (1956)

[12] Teghtsoonian, R., Teghtsoonian, M., and Canévet, G., "The perception of waning signals: Decruitment in loudness and perceived size", *Perception & Psychophysics* **62**, 637-646 (2000)

[13] Canévet, G., Teghtsoonian, R., and Teghtsoonian, M., "A comparison of loudness change in signals that continuously rise or fall in amplitude", *Acta Acustica united with Acustica* **89**, 339-345 (2003)

[14] Schlauch, R. S., "A cognitive influence on the loudness of tones that change continuously in level", *Journal of the Acoustical Society of America* **92**, 758 (1992)

[15] Teghtsoonian, R., Teghtsoonian, M., and Canévet, G., "Sweep-induced acceleration in loudness change and the "bias for rising intensities"", *Perception and Psychophysics* **67**, 699-711 (2005)

[16] Scharf, B., Loudness adaptation, in *Hearing Research and Theory*, J.V. Tobias and E.D. Schubert, Editors. 1983, Academic Press: Orlando.

[17] Neuhoff, J. G., "'Perception of changes in loudness': Reply", *Nature* **398**, 673-674 (1999)

[18] Neuhoff, J. G., "Perceptual bias for rising tones", *Nature* **395**, 123-124 (1998)

[19] Olsen, K. N., Stevens, C. J., and Tardieu, J., "Loudness change in response to dynamic acoustic intensity", *Journal of Experimental Psychology: Human Perception and Performance* **36**, 1631-1644 (2010)

[20] Neuhoff, J. G., "An adaptive bias in the perception of looming auditory motion", *Ecological Psychology* **13**, 87-110 (2001)

[21] Jenison, R. L., "On acoustic information for motion", *Ecological Psychology* **9**, 131-151 (1997)

[22] Bach, D. R., Neuhoff, J. G., Perrig, W., and Seifritz, E., "Looming sounds as warning signals: The function of motion cues", *International Journal of Psychophysiology* **74**, 28-33 (2009)

[23] Bach, D. R., Schachinger, H., Neuhoff, J. G., Esposito, F., Di Salle, F., Lehmann, C., et al., "Rising sound intensity: An intrinsic warning cue activating the amygdala", *Cerebral Cortex* **18**, 145-150 (2008)

[24] Hall, D. A. and Moore, D. R., "Auditory neuroscience: The salience of looming sounds", *Current Biology* **13**, R91-R93 (2003)

[25] Seifritz, E., Neuhoff, J. G., Bilecen, D., Scheffler, K., Mustovic, H., Schachinger, H., et al., "Neural processing of auditory looming in the human brain", *Current Biology* **12**, 2147-2151 (2002)

[26] Neuhoff, J. G., Planisek, R., and Seifritz, E., "Adaptive sex differences in auditory motion perception: looming sounds are special", *Journal of Experimental Psychology: Human Perception and Performance* **35**, 225-234 (2009)

[27] Rosenblum, L. D., Wuestefeld, A. P., and Saldana, H. M., "Auditory looming perception: Influences on anticipatory judgments", *Perception* **22**, 1467-1482 (1993)

[28] Schiff, W. and Oldak, R., "Accuracy of judging time to arrival: Effects of modality, trajectory, and gender", *Journal of Experimental Psychology: Human Perception and Performance* **16**, 303-316 (1990)

[29] Canévet, G., Scharf, B., Schlauch, R. S., Teghtsoonian, M., and Teghtsoonian, R., "Perception of changes in loudness", *Nature* **398**, 673 (1999)

[30] Olsen, K. N. and Stevens, C. J., "Perceptual overestimation of rising intensity: Is stimulus continuity necessary?", *Perception* **39**, 695-704 (2010)

[31] Susini, P., Meunier, S., Trapeau, R., and Chatron, J., "End level bias on direct loudness ratings of increasing sounds", *Journal of the Acoustical Society of America* **128**, EL163-EL168 (2010)

[32] Canévet, G., Teghtsoonian, M., and Teghtsoonian, R., "Assimilation and asymmetry of loudness change in magnitude-estimation measurements", *Acta Acustica united with Acustica* **89**, 530-539 (2003)

[33] Susini, P., McAdams, S., and Smith, B. K., "Global and continuous loudness estimation of time-varying levels", *Acta Acustica united with Acustica* **88**, 536-548 (2002)

[34] Susini, P., McAdams, S., and Smith, B. K., "Loudness asymmetries for tones with increasing and decreasing levels using continuous and global ratings", *Acta Acustica united with Acustica* **93**, 623-631 (2007)

[35] Jahnke, J. C., "Serial position effects in immediate serial recall", *Journal of Verbal Learning and Verbal Behavior* **2**, 284–287 (1963)

[36] Olsen, K. N. and Stevens, C. J., "Forward masking of dynamic acoustic intensity: Effects of intensity region and end-level", *Perception* **41**, 594-605 (2012)

[37] Ries, D. T., Schlauch, R. S., and DiGiovanni, J. J., "The role of temporal-masking patterns in the determination of subjective duration and loudness for ramped and damped sounds", *Journal of the Acoustical Society of America* **124**, 3772–3783 (2008)

[38] Oxenham, A. J., "Forward masking: Adaptation or integration?", *Journal of the Acoustical Society of America* **109**, 732-741 (2001)

[39] Kuwano, S. and Namba, S., "Continuous judgment of level-fluctuating sounds and the relationship between overall loudness and instantaneous loudness", *Psychological Research* **47**, 27-37 (1985)

[40] Dean, R. T., Bailes, F., and Schubert, E., "Acoustic intensity causes perceived changes in arousal levels in music: An experimental investigation", *PloS one* **6**, e18591 (2011)

[41] Olsen, K. N., Dean, R. T., and Stevens, C. J., "A continuous measure of musical engagement contributes to prediction of perceived arousal and valence", *Psychomusicology: Music, Mind, and Brain* **24**, 147-156 (2014)

[42] Geringer, J. M., "Continuous loudness judgments of dynamics in recorded music excerpts", *Journal of Research in Music Education* **43**, 22-35 (1995)

[43] Bailes, F. and Dean, R. T., "Comparative time series analysis of perceptual responses to electroacoustic music", *Music Perception* **29**, 359-375 (2012)

[44] Dean, R. T. and Bailes, F., "Time series analysis as a method to examine acoustical influences on real-time perception of music", *Empirical Musicology Review* **5**, 152-175 (2010)

[45] Olsen, K. N., Stevens, C. J., Dean, R. T., and Bailes, F., "Continuous loudness response to acoustic intensity dynamics in melodies: Effects of melodic contour, tempo, and tonality", *Acta Psychologica* **149**, 117-128 (2014)

[46] Meddis, R., "Auditory-nerve first-spike latency and auditory absolute threshold: a computer model", *Journal of the Acoustical Society of America* **119**, 406-417 (2006)

[47] Meddis, R., Hewitt, M. J., and Shackleton, T. M., "Implementation details of a computation model of the inner hair-cell auditory-nerve synapse", *Journal of the Acoustical Society of America* **87**, 1813 (1990)

[48] Smith, R. and Brachman, M., "Adaptation in auditory-nerve fibers: a revised model", *Biological cybernetics* **44**, 107-120 (1982)

[49] Sumner, C. J., Lopez-Poveda, E. A., O'Mard, L. P., and Meddis, R., "Adaptation in a revised inner-hair cell model", *Journal of the Acoustical Society of America* **113**, 893-901 (2003)

[50] Hancock, P. and Manser, M., "Time-to-contact: More than tau alone", *Ecological Psychology* **9**, 265-297 (1997)

[51] Manser, M. and Hancock, P., "Influence of approach angle on estimates of time-to-contact", *Ecological Psychology* **8**, 71-99 (1996)