# LOUDNESS "FATIGUE" WITH TWO EARS BUT NOT WITH ONE: SIMULTANEOUS DICHOTIC LOUDNESS BALANCE (SDLB) EXPLAINED

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## Abstract

*In SDLB (1950 onwards), the loudness contribution from the continually exposed "fatiguing" ear is matched by adjusting the intensity of an intermittent stimulus at the other ("comparison") ear. The latter intensity declines, indicating "loudness fatigue". However, the loudness of a continuous well-supra-threshold stimulus to one ear (with the other in quiet) does not diminish. Here is a quandary, presently resolved through a novel model dependent upon (1) the aforementioned non-fatiguing, and (2) the olivocochlear bundle, which "turns down the volume" in the ear opposite to one experiencing stimuli. The model explains how "fatigue" varies with stimulus variation, revealing "fatigue" as an SDLB artifact.*

The papers cited here include crucial early contributions to SDLB. As such, some are quoted, to capture the atmosphere of the work while explaining it succinctly.

SDLB allegedly measures "the decrease in the loudness of a steady acoustic stimulus *during* its presentation" (Egan, 1955, p. 111; original italics), called perstimulatory fatigue. Note SDLB's purported motivation (Small, 1963, p. 289):

> If a pure tone is presented to a listener continuously and at the end of five minutes he is asked if the stimulus sounds differently than it did in the beginning, his usual response is "no, it sounds the same". The perceived loudness of the stimulus remains very nearly unchanged. It is as though the listener had neither an internal loudness standard nor an effective memory and thus is able to compare the loudness in a particular segment of time only with the loudness of the stimulus in the immediately preceding segment – an imperceptible change. The key to the perception and measurement of a loudness decrement under these circumstances seems to be the availability of a comparison stimulus.

SDLB uses a comparison stimulus. Egan (1955, p. 111) explained while introducing jargon:

> A fatiguing stimulus having constant spectral characteristics is presented to one ear. A comparison stimulus whose intensity the listener can control is simultaneously presented to the other ear. During the simultaneous dichotic stimulation the listener adjusts the intensity of the comparison stimulus until it appears as loud as the fixed, fatiguing stimulus. After this loudness balance the comparison stimulus is turned off, but the fatiguing stimulus continues to sound. Later the comparison stimulus is again briefly presented for a loudness balance with the fatiguing stimulus. In this way the temporal course of the decline in loudness of the fatiguing stimulus may be obtained.

Unfortunately, the meaning of "fatiguing" and "comparison" has sometimes been reversed. Further, "test ear" has been used for either ear. Here, in an attempt at clarity, the ear receiving

the "fatiguing" stimulus will be called "ipsilateral" and the ear receiving the comparison will be called "contralateral". The terms "fatiguing" and "comparison" will still be used when needed. A single experimental "run" in classic SDLB was described by Egan (1955, p. 112):

> The temporal sequence of the stimuli in measuring perstimulatory fatigue was as follows. The fatiguing and the comparison stimuli were presented together for 20 seconds, during which time the listener adjusted the intensity of the comparison stimulus for a loudness balance. Both stimuli were then turned off and the listener called out his [attenuator] setting. Forty seconds later both stimuli were presented again for another loudness balance. After cycle was repeated several times, the fatiguing stimulus was left on. During this fatiguing period, the comparison stimulus was presented every minute for 20 seconds beginning on the minute. The recovery from perstimulatory fatigue was traced by turning off both the fatiguing and comparison stimuli for 40 seconds and then presenting both stimuli for another loudness match.

The comparison periods respectively preceding and following "perstimulatory" were deemed "prestimulatory" and "poststimulatory". Figure 1 (after Egan, 1955) shows these three stages. The per- or post-stimulatory "fatigue" indicated by a matching comparison stimulus intensity is the latter's dB SPL subtracted from the average prestimulatory comparison dB SPL.

Small and Minifie (1961, p. 1028) noted that "Unfortunately, it takes an appreciable interval to obtain a loudness balance"; Egan's (1955) subjects admittedly used all of each of their allotted 20 sec. Also, a subject's attenuator was always set to its minimum between loudness matches, and further, an arbitrary amount of attenuation, unknown to the subject, was introduced by the experimenter. Thus, "As a consequence of the attenuation introduced into the [attenuator] pads of the experimenter and observer, on any given [loudness] balance the intensity [*sic*] of the comparison stimulus at its onset was either completely inaudible or relatively weak" (Thwing, 1955). Each subject was thus obliged to begin each adjustment session by raising the intensity of the comparison stimulus.
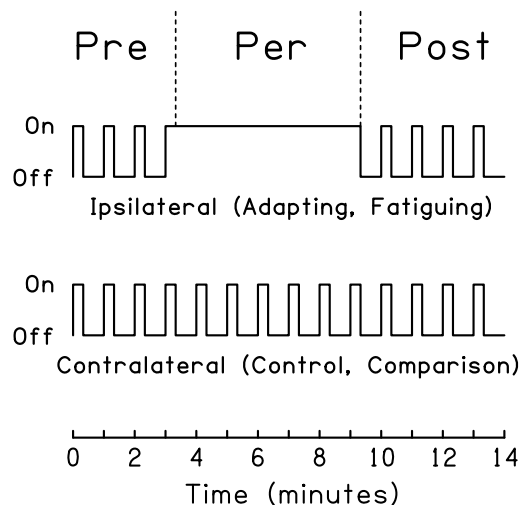
Figure 1. Stimulus schedule during a typical SDLB run (see text).

In SDLB, perstimulatory ipsilateral "fatigue" increases with ipsilateral stimulus duration, although its rate-of-change decreases with time such that it appears to asymptote (e.g., Hood, 1950; Carterette; 1955; Egan, 1955; Thwing, 1955; Jerger, 1957; Small & Minifie, 1961; Sergeant & Harris, 1963; Fraser, Petty, & Elliott, 1970; Petty, Fraser, & Elliott, 1970; Stokinger, Cooper, & Meissner, 1972). Time-to-asymptote appears to be at least 5 min, and perhaps more than 10 min, for stimuli ≥80 dB SPL, and it increases with ipsilateral intensity (Hood, 1950; Egan, 1955; Carterette, 1955; Jerger, 1957; Petty et al., 1970). The greatest "fatigue" occurs within the first 1-2 minutes. However, SDLB studies (e.g., Petty et al., 1970; Stokinger, Cooper, Meissner, & Jones, 1972) and monaural studies (e.g., Mirabella, Taub, & Teichner, 1967; Wiley, Small, & Lilly, 1973) imply that the "fatigued" ear does not fatigue when the comparison ear is in quiet. What, then, is "fatigue" in SDLB? This paper presents and validates a new model.

## The physiology of "fatigue": the olivocochlear bundle (OCB) in SDLB

An ear's contribution to loudness is presumed to rise with (1) the number of primary "afferent" neurons (those carrying signals brain-wards) which are firing above their spontaneous rates, and (2) their firing rates (summed in Nizami & Schneider, 1997). An ongoing tone at one ear evokes simultaneous firing (for at least 10 minutes, with a slight firing rate decline) in the OCB of "efferent" neurons (those carrying signals "away from" the brain, periphery-wards) which project to the *opposite* ear, effectively "turning down" that opposite ear's "volume" as if same-frequency tones there had dropped as much as 24 dB (even more may be possible). Olivocochlear efferents are found at all characteristic (i.e., most sensitive) frequencies of primary afferents, showing a variety of thresholds, allowing smooth and progressive suppression.

Figure 2 illustrates OCB involvement in SDLB, as follows. Contributions to loudness from each ear add with equal weight to create the overall loudness. Subjects equate the contributions by adjusting the "control" (contralateral) ear stimulus intensity during SDLB adjustment sessions. In Fig. 2, at the bottom, is a linear time scale for all of Fig. 2. The figure's upper and middle frames respectively show the ipsilateral and contralateral ears' equated contributions to loudness. Stimulus absence is taken as zero intensity. Between contralateral-stimulus presentations, loudness is due only to the ipsilateral stimulus, and does not diminish. The gaps between contralateral stimuli allow the ipsilateral contribution to recover from any contralateral-evoked reduction. The figure's bottom frame indicates the *average* stimulus intensity at the contralateral ear, "average" because the subject adjusts intensity up and down during the contralateral stimulus' comparatively brief appearances.

Each ear accesses its separate OCB; stimulus at an ear induces efferent firing which affects the opposite ear. In SDLB, the perstimulatory ipsilateral stimulus progressively "turns down the volume" at the contralateral ear. To compensate, the initial magnitude of the contralateral stimulus intensity must be set increasingly *higher* over successive adjustment sessions (Fig. 2). In response, the *ipsilateral* ear desensitizes, momentarily reducing its contribution to loudness. By the end of each adjustment session, the subject must match that reduced contribution, by reducing the average stimulus intensity from its initial peak to a final steady setting. Typical adjustment sessions of 10 sec (Hood, 1950) to 20 sec (Egan, 1955) are plenty to allow changes in the degree of "volume turn-down" by the OCB, whose initiation has time constants in the hundred-millisecond range.
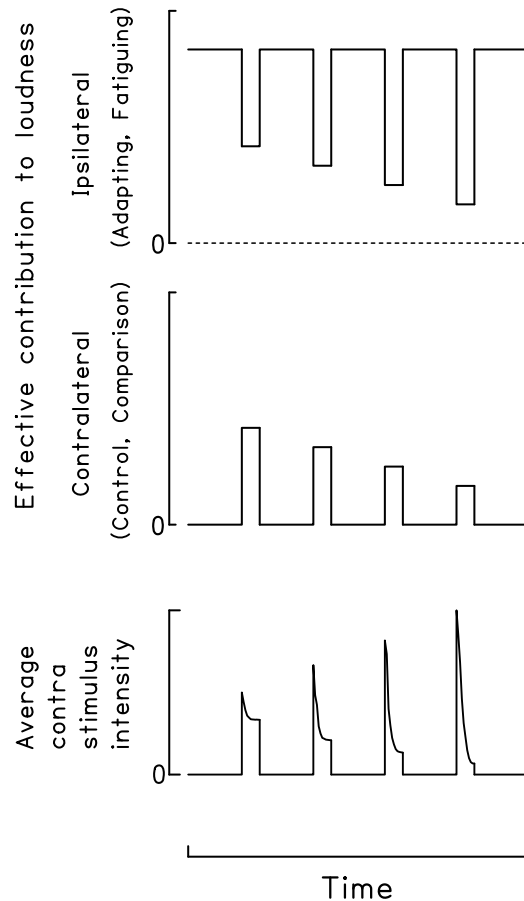
Figure 2. Model of events during the perstimulatory stage of an SDLB run (see text).

**Predictions of the model, and evidence consistent with them**

Various predictions emanate from the present model, regarding:

(1) *SDLB experiments whose loudness-matching method mimics the changes occurring when subjects make attenuator adjustments*. "Fatigue" behavior should mimic that found in the classic SDLB experiments which involved subjects making attenuator adjustments over 10-20 sec. *Confirmed*: Some experiments from the late 1960s onwards used "the method of constant stimuli", in which the "comparison" tones were made as brief as possible in the belief that "self-fatiguing" by contralateral stimuli could be avoided. See for example Stokinger and Studebaker (1968), Petty et al. (1970, Fig. 4), Stokinger, Cooper, and Meissner (1972), Stokinger, Cooper, Meissner, and Jones (1972), Bray, Dirks, and Morgan (1973), and Dirks, Morgan, and Bray (1974), whose comparison-stimulus durations were respectively 1 sec, 1 sec, 0.2 sec (or 2 sec or 1 sec), 0.2 sec, 3 sec, or 0.3 sec. Of those investigators, only Bray et al. (1973) had subjects perform traditional attenuator adjustments (3 sec), which proved difficult. Such briefness of comparison stimuli does not allow subjects enough time to adjust intensity. Hence, the comparison stimulus was kept at a fixed intensity on any single

presentation, the subject signaling whether it was louder or not than the "fatiguing" stimulus, the experimenter then adjusting its intensity in order to cross back and forth, on a series of successive judgments, the intensity that putatively provided equal loudness. Each such determination would be followed by a rest period for the subject and experimenter while the "fatiguing" stimulus continued to play to the subject.

(2) *Post-stimulatory recovery*. Post-stimulatory, the phenomena of Fig. 2 will reverse, as will "fatigue". *Confirmed*: Carterette (1955, Fig. 3); Egan (1955, Fig. 2); Thwing (1955, Fig. 3).

(3) *The "duty cycles" ([stimulus duration] divided by [stimulus duration plus recovery interval]) of the "fatiguing" and comparison stimuli*. The lower the "duty cycle" of an intermittent squarely-amplitude-modulated stimulus, the more the time for the opposing ear to recover from OCB-mediated "volume turn-down". Thus, an intermittent ipsilateral stimulus should have less accumulated effect on the contralateral ear than a steady one, such that, in return, perstimulatory ipsilateral "fatigue" at any time should be less than for a steady ipsilateral tone, but should increase with duty cycle. *Confirmed*: Carterette (1955). Conversely, a *contralateral* duty-cycle increase "turns down the volume" at the ipsilateral ear, reducing that ear's effect upon the contralateral ear. If duty cycle is *identical* at both ears, the contralateral ear (when its stimulus is absent in-between matches) will be the less influential one. *Confirmed*: Sergeant and Harris (1963); Stokinger, Cooper, and Meissner (1972). (3a) *Contralateral stimulus duration*: (3aa) *Stimuli long enough to be continuously attenuated by the subject*. Shortening the adjustment session duration (e.g., from 20 sec to 10 sec) rushes the subject, who exaggerates the initial, peak contralateral stimulus intensity, which exaggerates "volume turn-down" at the ipsilateral ear, necessitating a lower matching intensity. *Confirmed*: Small and Minifie (1961); compare Hood (1950, Fig. 15) to Thwing (1955, Figs. 3, 4) to Egan (1955, Table IV) for "fatiguing" by 1 kHz at 80 dB SPL. (3aaa) If *perstimulatory ipsilateral stimulus intensity is increased* between runs, the subject follows the same train of adjustments, with the same effects. *Confirmed*: Hood (1950, Fig. 15); Jerger (1957); Stokinger and Studebaker (1968); Petty et al. (1970). (3ab) *Contralateral stimuli too short to allow continuous attenuation by the subject*. The briefer such stimuli, the less time for "volume turn-down" at the ipsilateral ear, hence the higher the matching contralateral intensity. *Confirmed*: Stokinger, Cooper, and Meissner (1972, "Experiment 1", 200 ms tones vs. 2 sec tones); Stokinger, Cooper, Meissner, and Jones (1972). (3ac) *Continuous perstimulatory contralateral stimulus*. Such (with contralateral matching sessions still done intermittently) allows the contralateral ear to continuously "turn down the volume" at the ipsilateral ear. The latter's contribution to loudness hence diminishes, during which the continuous ipsilateral stimulus nonetheless "turns the volume down" at the *contralateral* ear. That effect, too, diminishes over time, thanks to the aforementioned "volume turn-down" at the *ipsilateral* ear. During adjustments, then, the subject's initial resetting of the ongoing contralateral stimulus intensity will not be as high – and the final resetting will not be as low – as for an *intermittent* contralateral stimulus, hence less ipsilateral "fatigue", if any. *Confirmed*: Small and Minifie (1961, Fig. 3). (3aca) *"Fatigue" during the pre*stimulatory period must obey the same principles, albeit involving far less accumulated "volume turn-down" at each ear. *Confirmed*: Egan (1955, Fig. 6), Fraser et al. (1970, Table 1), and Petty et al. (1970, Table 1) show contralateral stimuli equated in intensity to same-frequency ipsilateral stimuli.

*(4) Momentarily dropping (not to zero) the ipsilateral perstimulatory intensity during the adjustment session*. This, combined with the usual manner of setting the initial peak contralateral stimulus intensity (Fig. 2), will produce an even lower matching contralateral loudness contribution (i.e., greater "fatigue"). *Confirmed*: Egan (1955, p. 115 with Fig. 4).

*(5) Waveform frequency of ipsilateral and contralateral tones*. OCB efferents have V-shaped "tuning curves" of the threshold for stimulated firing versus the stimulus frequency, like those of primary afferents. Hence "fatigue", *as measured momentarily using tones of the same*

*frequency to each ear during each adjustment session*, should progressively decrease as the contralateral-tone frequency diverges from the (otherwise fixed) frequency of the ipsilateral tone, according to an inverted "tuning curve". *Confirmed*: Thwing (1955); Fraser et al. (1970); Bray et al. (1973). When *ipsilateral and contralateral tones have the same frequency*, "fatigue" should be greatest for frequencies for which the OCB innervation at the organ of Corti is densest, namely, mid-to-high frequencies. *Confirmed*: Jerger (1957).

 (6) *Presentation of contralateral stimulus after "fatiguing" stimulus*. Any contralateral-ear influence on the ipsilateral ear is now irrelevant; subjects hence equate stimulus intensities at the two ears. *Confirmed*: Egan and Thwing (1955); Petty et al. (1970); Fraser et al. (1970).

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