The influence of fundamental frequency on perceived duration: A replication study

Marvin Li, Chayra Montoya

Cognitive Science and Psychology Undergraduate Lab @ Berkeley

Undergraduate Mentor: Ashish Ramesh

Graduate Student Mentor: Zuzanna Balewski

Acknowledgements

This work was supported by the Cognitive Science and Psychology Division of the Undergraduate Laboratory at Berkeley (ULAB). We would like to thank Professor Mark D'Esposito for acting as the faculty mentor for this division, Zuzanna Balewski for acting as our graduate student mentor, and the board of the Cognitive Science and Psychology Division of ULAB for supporting us through this project.

Abstract

The following study examines the relation between perceived duration and the intensity and fundamental frequency of sounds. Sounds with higher fundamental frequency (the lowest frequency of a periodic waveform) and greater intensity are judged to have longer duration. However, it is not known if fundamental frequency, intensity, or both affect the perceived duration, and to what extent. The purpose of this study is to find out the variance in contribution of both fundamental frequency and intensity to perceived duration through two forced choice tasks. Through replication, we found that fundamental frequency does in fact have a significant positive effect on perceived duration while intensity did not. Future research may focus on testing these results among different language groups, and applying these results to an understanding of communication and language.

Introduction

A sinusoid is a sound wave that can be characterized by the sine function; it can be characterized by three parameters: intensity (amplitude), frequency (pitch), and duration. The amplitude of a sinusoidal sound wave is defined as the how much of a difference in pressure the sound makes, and is heard as the loudness of a sound; this is usually measured in decibels (dB). Frequency is how often the wave repeats itself in a second, typically measured in Hertz (Hz), and is heard as the pitch of the sound. The fundamental frequency of a sound is the lowest frequency of the soundwave.

The actual and perceived duration of a sound differ, and depend on its intensity and fundamental frequency: higher intensity leads to greater perceived duration, and higher fundamental frequency leads to greater perceived loudness. Disentangling how intensity and fundamental frequency affect perceived duration is salient because the two are not independent of each other, and the interaction of all three elements is linguistically and phonetically relevant (Dawson et al., 2017). The two forced choice discrimination experiments in the study address this by simultaneously varying intensity, duration, and fundamental frequency of two sounds, and asking participants to judge duration and intensity differences. By comparing the influences of these three parameters, it is possible to determine whether fundamental frequency's effect of loudness alone is enough to explain perceived duration. We hypothesized that intensity, duration, and fundamental frequency affect the perception of intensity and duration, and while original study found all these factors to significantly affect perceived intensity and duration, this replication only did so for the latter two.

The researchers recruited eleven native monolingual Finnish speakers to participate in forced choice discrimination tasks, one for evaluating intensity discrimination and the other for evaluating duration discrimination. This was set up with a block design, in which the stimuli were grouped into blocks based on what parameter was being evaluated. There were two blocks, one for intensity discrimination and the other for duration discrimination, with each one presenting 300 pairs of stimuli, and the order of the blocks was randomized between participants. After each pair, the participants were asked to indicate which of the two stimuli was louder or longer. They typed *a* (on a Swedish/Finnish keyboard) to indicate the first sound, *x* to indicate the second, and could also choose to opt out or say that they did not know.

Fig. 1:

A diagram of the block design used in the original experiment, showing the time between each of the sounds; the order of the blocks was randomized for participants.

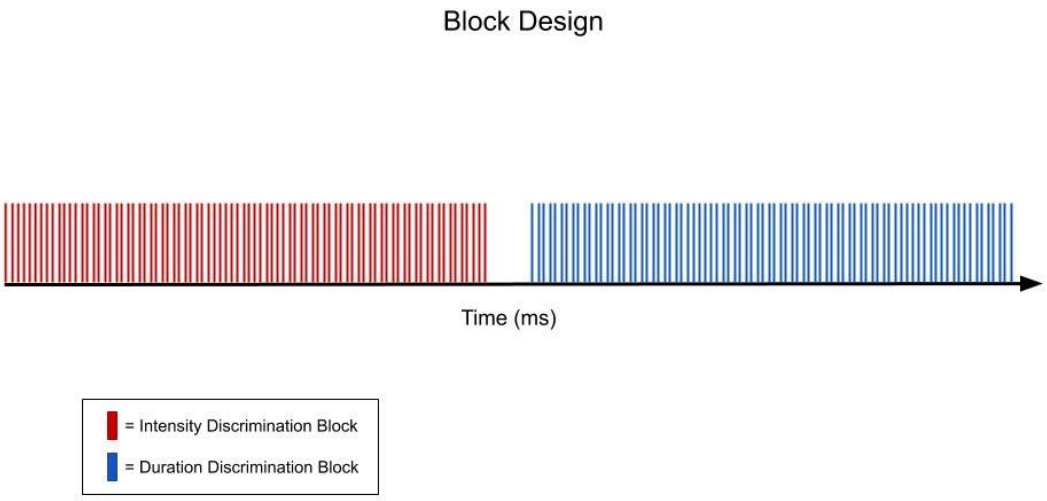
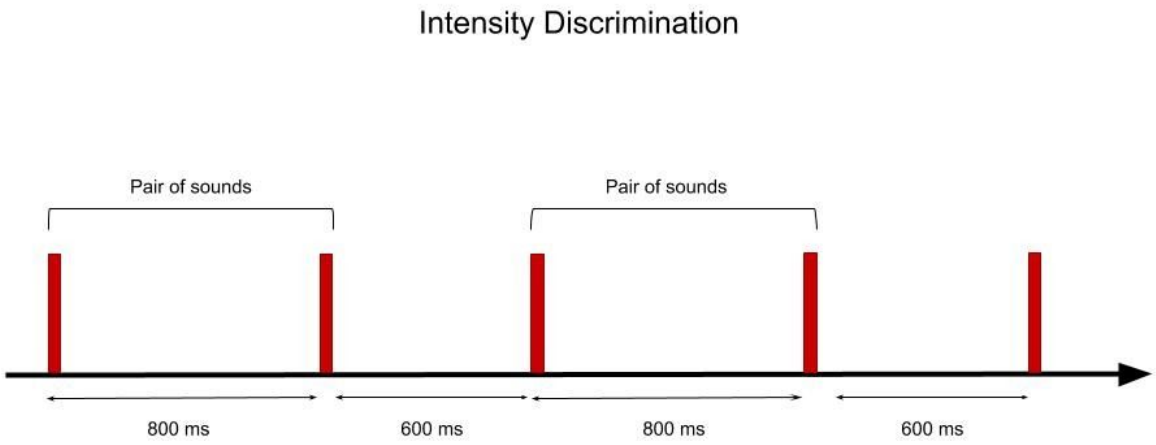


Fig. 2: *A diagram illustrating the temporal presentation of select stimuli in the intensity discrimination block.*



Every sound used as a stimulus varied in terms of its duration, fundamental frequency (f_0), dynamic f_0 interval, and intensity. These parameters were all randomly generated for each sound from a truncated normal probability distribution. The durations of the sounds varied from 150 ms to 450 ms, and the intensity levels varied between 60 dB and 72 dB. The researchers created each sound with a sawtooth wave, which is rich in spectral content, meaning that it contains many frequencies layered on top of its fundamental frequency. This makes it possible to filter out the fundamental frequency while retaining its effect, which is done in order to remove confounding effects from the tone at the fundamental frequency.

Fig. 3:

A diagram of an example of the original sound wave (A) and the resultant sound wave after a filter is applied (B). Taken from the original study.

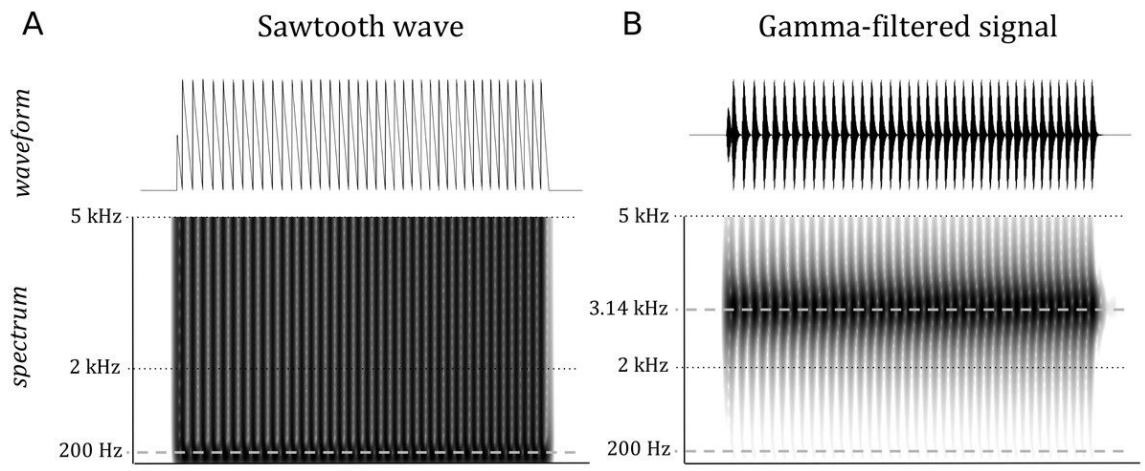
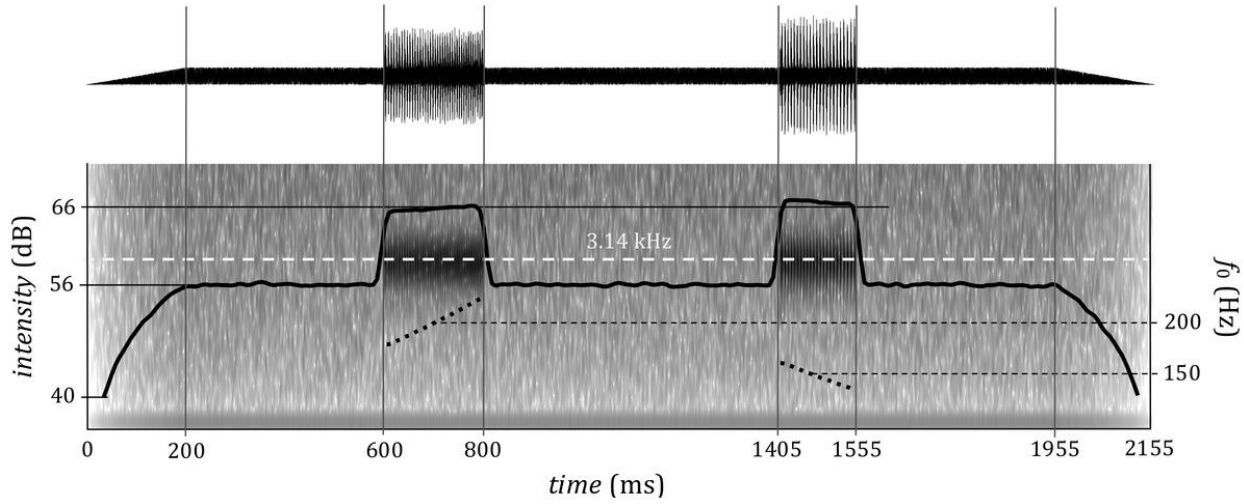


Fig. 4:

A spectrogram of an example trial in which two sounds are presented with a 605 ms spacing between them. Taken from the original study.



Methods

In terms of our replication methods, we used the lme4 package in R to create mixed-effect logistic models, as this was the package that the original study authors used. This was possible by using the instructions from "Using lme4" (Chang 2010) as a guide to create the appropriate models and match the results to what the original study authors were able to provide.

In particular, the lme4 package was used to create logistic regression by means of the "logit" link function, with duration difference, intensity difference, and frequency difference as fixed effects, and subject as a random effect. This model was compared with another model with the same fixed effects, but with intensity difference as an additional random effect using the "anova" function in the lme4 package; the book *YaRrr! The Pirate's Guide to R* (Phillips, 2017) served as a guide for this comparison.

Results

Intensity Discrimination

The effects of duration and frequency differences were both positive and significant, suggesting that increasing either one is correlated with increased perceived loudness (Table 1). The original study's results, however, had positive and significant effects of intensity, duration, and frequency differences. When fitting the logistic regression model for each of the participants, the effect of duration difference was positive and significant in most participants, while the effect of intensity difference was positive and significant for only one of the participants (Fig. 5, Table 2). This differs from the original study's results, in which the effect of duration and intensity difference was significant and positive for all participants.

When increasing the intensity level of the first sound presented by 1 dB, the model reports an increase of about 0.0084 in the resulting response. Similarly, this effect can also be attained by lengthening the duration of the first sound by 1.8 ms ($4.65349 \times 0.0018 \approx 0.0084$), or increasing the fundamental frequency by 0.765 semitones ($0.011 \times 0.765 \approx 0.0084$).

By comparing the deviance of this model to the deviance of a null model which includes only random intercepts for the subjects, the deviance of the experimental model reduces approximately 6.75%. This shows that the model provides a better fit to the data than the null model ($p < 2.2*10^{-16}$ by Likelihood-ratio test).

Fig. 5:

Per-subject effects of duration difference, intensity difference, and frequency difference (left to right) on response for intensity discrimination. P-values for each subject are overlaid in red.

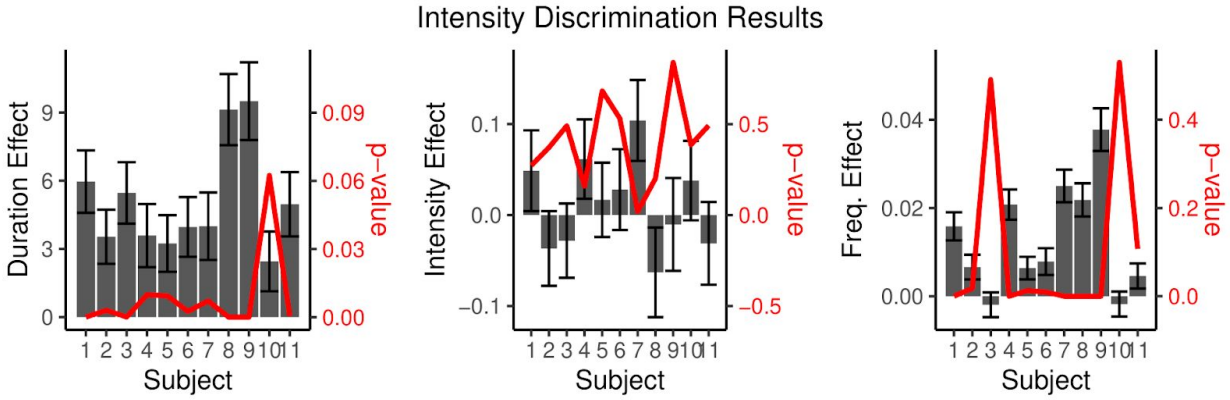


Table 1: Mixed effects model fitted to the responses of *intensity discrimination* with frequency range difference calculated as the difference between the raw values of the dynamic f_0 ranges.

Effect	Size	Error	*z*-value	*p*-value
Intercept	0.1106957	0.0556963	1.987	0.0469
Duration difference	4.6534900	0.3963540	11.741	<2e-16
Intensity difference	0.0084159	0.0128619	0.654	0.5129
Frequency difference	0.0110486	0.0008872	12.453	<2e-16

Table 2: Effect estimates and significances of the logistic models effects model fitted for the individual subjects for *intensity* discrimination (difference between absolute frequency ranges). Significance codes: 0<*** < 0.001<** < 0.01<* < 0.05.

Subject	Intercept	Duration difference	Intensity Difference	Frequency Difference
1	0.1513431895	5.46311783905447***	-0.02817376864	-0.001926131145
2	0.562670826048511***	3.58871752959396**	0.06143806122	0.0207903021757834***
3	-0.134034432	3.23892057141012**	0.01671747464	0.00638405280885875*
4	0.1566782894	3.96662803023915**	0.02794362594	0.00786564980925411**
5	0.2100467095	3.99847523289165**	0.103982489455141*	0.0249924344795979***
6	0.1438630076	9.12966907125729***	-0.06293191546	0.0218389035840898***
7	0.2232830286	9.50117874352221***	-0.01032633248	0.0377726884943749***
8	-0.1367695469	2.45179364	0.03787770738	-0.001773046372
9	-0.1388241441	4.96625392224125***	-0.03123679802	0.004592185543
10	0.1855248497	5.96108712151908***	0.04873937008	0.0158519777299048***
11	0.1792028838	3.5343831168899**	-0.03672425808	0.00662010843590686*

Duration Discrimination

Based on our replication tables below, the participants' duration judgements of sound stimuli were affected equally by a 28 ms duration increase, a 1 dB increase in intensity, and a 5.9 semitone increase in fundamental frequency (Table 3). Furthermore, the frequency modulation effect on duration difference was significantly positive for all subjects excluding subjects 9 and 11. For intensity difference, the effect was only significant for subjects 1, 3, and 9, and the difference varies in terms of positive and negative difference. The effect on fundamental frequency differences were significantly positive for all subjects besides subject 11 (Fig. 6, Table 4).

By comparing the deviance of this model to the deviance of a null model which includes only random intercepts for the subjects, the deviance of the experimental model reduces approximately 42.40%. This shows that the model provides a better fit to the data than the null model ($p < 2.2*10^{-16}$ by Likelihood-ratio test).

Fig. 6:

Per-subject effects of duration difference, intensity difference, and frequency difference (left to right) on response for duration discrimination. P-values for each subject are overlaid in red.

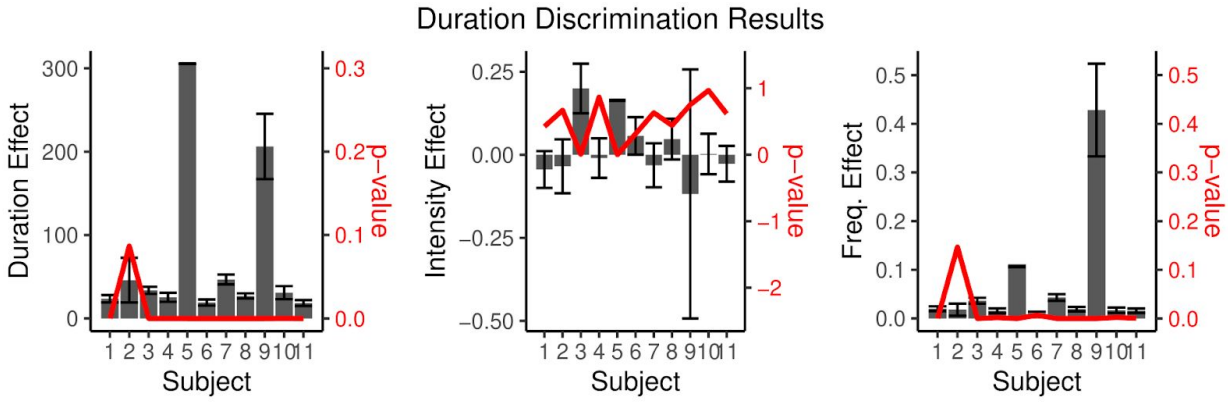


Table 3: Mixed effects model fitted to the responses of *duration discrimination* with frequency range difference calculated as the difference between the raw values of the dynamic f_0 ranges.

Effect	Size	Error	z-value	p-value
Intercept	0.473407	0.183141	2.585	0.00974
Duration difference	25.538908	0.906263	28.180	<2e-16
Intensity difference	0.018411	0.017292	1.065	0.28700
Frequency difference	0.019572	0.001253	15.623	<2e-16

Table 4: Effect estimates and significances of the logistic models effects model fitted for the individual subjects for *duration* discrimination (difference between absolute frequency ranges). Significance codes: 0<*** < 0.001<** < 0.01<* < 0.05.

Subject	Intercept	Duration difference	Intensity Difference	Frequency Difference
1	2.118005659***	33.68441136***	0.1995971774**	0.03647950467***
2	0.8139363881***	25.35683752***	-0.009812712089	0.01585633758**
3	-1.80779929***	305.5558874***	0.1640253546***	0.1069318913***
4	-0.1120834126	19.11135371***	0.05681608207	0.009957941198**
5	-0.1627780469	46.73034432***	-0.03163760509	0.0430823464***
6	0.4875499631**	26.99091463***	0.0471675165	0.0191133184***
7	11.14568009*	206.2976163**	-0.1178435021	0.4284110672**
8	0.1674486052	30.92401744***	0.002357771175	0.01695917017**
9	0.8803313754***	18.49620166	-0.02689940549***	0.01590237448***
10	0.6388755637***	23.6380582***	-0.04434615944	0.0199154973***
11	-0.4324082512	45.89839799	-0.03459950293	0.01806664681

Discussion & Analysis

The experimental methods involved the separation of the effects of intensity and fundamental frequency, but the fundamental frequency still had a significant effect on the perceived duration of sounds. These results suggest that fundamental frequency affects the perceived duration of a sound separately from intensity. This is what the original study found, though the significance of the parameters differed, which may be due to the omission of dynamic fundamental frequency information from the dataset. Though they did report that this parameter's effect was not significant, the data may have affected some of the other parameters in our model; the original study notes a difference about effect sizes between models that captured this dynamic frequency information in different ways.

While our results failed to find a significant and positive effect of intensity difference in intensity discrimination and duration discrimination, the original study achieved such an effect, in both discrimination tasks. This difference may be due to a difference in scales used in the dataset, because the original paper mentions that the range of intensity was 60 dB and 72 dB, but the values in the dataset are approximately between -8 and 8, with no units indicated. Especially given that we found significance for the other parameters of the models, it may be possible that the discrepancy was due to this.

In terms of duration discrimination, all but one participant in the intensity discrimination task and for all but two participants in the duration discrimination task had significant and positive effects. These results suggest that fundamental frequency do in fact have an overall positive effect on perceived duration of sound stimuli, while the effects of intensity on perceived duration is more ambiguous, with both positive and negative effects. This in turn suggests that fundamental frequency is the sole influencer on perceived duration. Similar to our replication, the original study showed that fundamental frequency difference showed significant positive effect on perceived duration across all subjects, demonstrating that increasing fundamental frequency increased the perceived sound duration. As mentioned previously, this is likely due to a difference in scales in the dataset for intensity measures, and the absence of dynamic f_0 level data.

The current study does have some important limitations. The study was conducted on a very small sample size of just 11 people, and although the actual number of trials was very large there was a somewhat small amount of per-subject variability. In addition, the study was conducted only on monolingual Finnish speakers, although the original study authors note that

similar results were also found in other languages. However, prior studies found that certain cues were not consistent across languages (Lehnert-LeHouillier, 2010) (Simko et. al., 2015). Further research would be needed in order to determine whether these conclusions are supported in larger-sample trials, or among different language groups.

Previous studies that investigate the effect of dynamic (changing) fundamental frequency on the perceived duration of a sound have found that it has a lengthening effect, regardless of an individual's native language (Cumming, 2011). In an attempt to pinpoint exactly how each of the parameters of fundamental frequency, intensity, and duration affect the subjective loudness and duration of a sound, a previous study showed that participants were forced to choose which of two sounds presented was either louder or longer; the sounds they were presented with varied in each of the three parameters (Dawson et al., 2017). The researchers found that fundamental frequency and intensity both affect how duration is perceived. Our study seeks to replicate their results using the data these researchers collected.

In contrast, other studies have also shown that language does have an effect on perceived duration. Researchers have found that English tones with non static patterns were judged to be longer than those with constant pitch. This suggests correlation between perceived duration and the extent and direction of the fundamental frequency movement (Simko et al., 2015) . A prior study by Lehnert-LeHouillier (2010) compared the influence of the lengthening effect on speakers of four languages without (Latin American Spanish) and with (German, Thai and Japanese) phonological vowel length contrast. The results showed that only Japanese participants judged stimuli with falling pitch as longer. However, for speakers of several languages from different languages families the higher pitched and louder stimuli were indeed judged as longer.

This shows that language does affect perceived duration, and from this result, it can be inferred that the original study's Finnish participants may be affected by their native language.

Conclusion

The purpose of this study was to find the effects of fundamental frequency, intensity, and duration of a sound on the perceived duration of a sound. We found that frequency and duration of a sound independently affect its perceived intensity and duration, in accordance with the findings of the original study. In particular, intensity of a sound was not found to significantly contribute to this, which contradicts the results of the original study. Such a result was likely due to a difference of intensity scales in the dataset, as well as the exclusion of dynamic fundamental frequency data. Further research could clarify these discrepancies by converting the intensity scale to the appropriate one, and ascertaining whether the exclusion of dynamic f_0 data substantially impacts data analysis. In addition, these trials could be replicated on a broader group of people with different native languages in order to test the variation in these results across different language groups.

References

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, 67(1), 1 - 48. doi:http://dx.doi.org/10.18637/jss.v067.i01

Berglund, B., Berglund, U., Ekman, G. and Frankehaeuser, M. (1969), The Influence of Auditory Stimulus Intensity on Apparent Duration. *Scandinavian Journal of Psychology,* 10: 21-26. doi:10.1111/j.1467-9450.1969.tb00003.x

Brigner, W. L. (1988). Perceived Duration as a Function of Pitch. *Perceptual and Motor Skills*, 67(1), 301–302. https://doi.org/10.2466/pms.1988.67.1.301

Cumming, R. (2011). The effect of dynamic fundamental frequency on the perception of duration. *Journal of Phonetics*, 39(3), 375-387 https://doi.org/10.1016/j.wocn.2011.01.004.

Chang L. 2010. Using lme4. http://www.u.arizona.edu/~ljchang/NewSite/papers/LME4_HO.pdf

Dawson C, Aalto D, Simko J, Vainio M. 2017. The influence of fundamental frequency on perceived duration in spectrally comparable sounds. *PeerJ* 5:e3734 https://doi.org/10.7717/peerj.3734

Gussenhoven, C., & Zhou, W. (2013). Revisiting pitch slope and height effects on perceived duration. *Proceedings of INTERSPEECH 2013: 14th Annual Conference of the International Speech Communication Association*, 1365 - 1369.

Jeon, J. Y., & Fricke, F. R. (1997). Duration of Perceived and Performed Sounds. *Psychology of Music*, *25*(1), 70–83. https://doi.org/10.1177/0305735697251006

Simko J, Aalto D, Lippus P, Włodarczak M, Vainio M.. (2015). Pitch, perceived duration and auditory biases: Comparison among languages. *The 18th international congress of phonetic sciences (ICPhS 2015)*. Glasgow. International Congress of Phonetic Sciences.

Kraemer, P.J., Brown, R.W., Randall, C.K. (1995). Signal intensity and duration estimation in rats. *Behavioural Processes*, 34(3), 265-268. https://doi.org/10.1016/0376-6357(95)00003-D.

Lake, J.I., LaBar, K.S., Meck, W.H. (2014). Hear it playing low and slow: How pitch level differentially influences time perception. *Acta Psychologica*, 149, 169-177. https://doi.org/10.1016/j.actpsy.2014.03.010.

Lehnert-LeHouillier, H. (2010). A cross-linguistic investigation of cues to vowel length perception. *Journal of Phonetics*, 38(3), 472-482. https://doi.org/10.1016/j.wocn.2010.05.003.

Phillips, N. D. (2017). Yarrr! The pirate's guide to R. *APS Observer*, *30*(3).

Rosen, S. M. (1977). The effect of fundamental frequency patterns on perceived duration. *Speech Transmission Laboratory—Quarterly Progress and Status Report*, *18*, 17-30.

Wittmann, M. (2013). The inner sense of time: how the brain creates a representation of duration. *Nat Rev Neurosci* 14, 217–223. https://doi.org/10.1038/nrn3452