Title
Using a Retro-Cue Paradigm to Probe the Temporal Precision of Auditory Memory Representations

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Publication Date
2024

University of California, Merced

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A Thesis submitted in partial satisfaction of the requirements for the degree of Master of Science

In

Cognitive and Information Sciences

By

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2024

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2024

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Acknowledgements:

I would like to thank my family, friends, and partner for always encouraging me and being there to listen. A special thank you to my sister and my partner for always showing me that I have their support. I want to thank my advisor Kristina Backer for all her patience and support as well as her excellent teaching skills. I could not have had a better advisor for my return to academia. I also thank the other graduate students that I collaborated with in class and work.

Abstract

Using a Retro-Cue Paradigm to Probe the Temporal Precision of Auditory Memory Representations

by David Parker for the partial satisfaction of the requirements for the degree

of Master of Science in Cognitive and Information Sciences, University of

California, Merced, 2024

Dr. Kristina Backer, Chair

Auditory attention to memory is often overlooked compared to the visual domain. Our aim is to expand research within the auditory domain using a retro-cue paradigm. This paradigm allows us to investigate the attentional effects on auditory short-term memory representations through the strengthening and/or focusing of these memory representations. This study involved tasking participants to use their short-term auditory memory, and a visual retro-cue to detect a change in a temporal auditory feature, using amplitude modulated (AM) sounds. The visual retro-cue was either informative or uninformative. An informative retro-cue is a stimulus that effectively reduces the working memory load of the participant in accordance with the memory probe task, thereby increasing accuracy, d', and/or response time on the memory probe task. The uninformative retro-cue is a stimulus that does not provide insight into the upcoming memory probe task and is used as a comparative baseline for the informative retro-cue. We hypothesized, based on past auditory research, that relative to uninformative retro-cues, the informative retro-cues would improve accuracy and response time, especially when detecting smaller changes in the probe's amplitude modulated AM rate relative to its original AM rate. However, due to various limitations, our hypothesis was unable to be verified. Future directions solving these limitations will hopefully be taken in the future. We found trends in the data that, when the limitations are addressed, may lead to significance once the study is revisited.

Introduction:

The present study explores the relationship between auditory attention and memory, shedding light on how retrospectively orienting attention can assist in retaining and recalling auditory information. Auditory attention to memory refers to the orienting of attention to focus on one or more sound representations held in memory. Why is this an important facet of auditory and memory research? To put it simply, sound is fleeting. Once the sound waves hit our ears, they are gone from the environment, and we cannot get them back. All that's left is the memory trace of what we heard. This is unlike visual stimuli which are often static in our environment. If we cannot remember the visual properties of an item in our environment, we can usually attend to it again, but the auditory signal disappears almost immediately. Therefore, simple tasks such as remembering verbal instructions require listeners to constantly orient our attention to the most recent auditory memory trace. Without this ability, we would be unable to retain these transient auditory signals.

There is a small literature of studies examining the neural processes that underlie one's ability to orient attention to auditory memory. Commonly this is done using a retro-cue paradigm (e.g., Backer et al. 2015, Lim et al. 2015). A typical retro-cue paradigm begins with stimuli being presented, which the participant is instructed to encode into memory. Then the retro-cue appears: a retro-cue is an attentional cue that can be either informative or uninformative. Finally, the memory probe occurs. Usually, the participant's task is to indicate whether the probe stimulus is different from the original version of that stimulus that was previously encoded on that trial. Informative retro-cues provide the participant with information that will assist in the memory probe portion of the trial by reducing the short-term memory load of the participant that was encoded at the beginning of the trial. Reducing the short-term memory load improved accuracy and/or response time on the memory probe task. Uninformative retro-cues do not provide insight on the upcoming memory probe, thus requiring the participant to continue to maintain all encoded representations in memory. The task performance measures are then compared within subjects between the uninformative cue condition and the informative cue condition. This comparison tells us if the informative retro-cue influenced task performance.

It has been shown that retro-cues not only facilitate selective attention within memory in the visual domain (Nobre, 2008), but they can do so in the auditory domain as well (Backer et al, 2015, Lim et al, 2015), as measured by enhanced accuracy, d', and/or response time to the probe stimulus on informative relative to uninformative retro-cue trials. Using the retro-cue paradigm, we can also determine how auditory attention to a particular stimulus representation held in working memory can improve the precision of that stimulus representation. For example, Lim et al. (2015) demonstrated that selectively attending to a particular auditory memory representation (via a retro-cue) can enhance the precision of a specific sound feature (i.e., pitch). The present study uses a similar design as Lim et al. (2015) to replicate and extend their finding, but the sound feature the present study focuses on is amplitude modulation (AM) rate. AM is the modulation of a sound wave by systematically varying its amplitude. An example would be: if a sound lasting 500ms has an AM rate of 10 Hz, then the sound wave would have 5 AM cycles in the 500ms. Asking a participant to detect a difference between, for example, a sound with a 10 Hz AM rate and the same sound but with a 10.5 Hz AM rate, requires precise temporal processing of these sound signals. Thus, by varying the extent to which the AM rate changes from the original stimulus to the probe stimulus in the context of a retro-cue task, we can then determine whether informative retro-cues enhance the temporal precision of the retrospectively attended auditory representation in memory. The question we pose is: "Does retrospectively cueing attention to an auditory stimulus improve accuracy and response time on an auditory attention to memory task, specifically one's ability to detect fine changes in AM rate?"

The investigation of attention to short-term memory (STM) in the auditory domain is a vital but often overlooked area of study. Our study examined the potential differences in auditory encoding and recall using the retro-cue paradigm for sequential sounds at varying AM rates. This informs us on whether directing attention to one auditory stimulus in working memory via an informative retro-cue can increase the temporal precision of the representation for that stimulus, relative to the uninformative retro-cue trials. An example would be: the informative retro-cue strengthening the representation with very small changes (±5% of the original AM Rate) in comparison to the uninformative retro-cue. Little is known about how the precision of auditory representations held in STM is affected by directing attention to a particular auditory STM representation. Further utilizing the retro-cue paradigm to study auditory attention to memory will potentially open pathways to more refined research questions, including the role of musical expertise.

Due to the limited literature on auditory attention to memory, one of our goals was to replicate the findings from Lim et al. (2015) and Backer & Alain (2012). Their findings showed that informative cues led to significantly faster response times to the probe stimulus and significantly increased accuracy on the task over the uninformative cues. Our other goal is to utilize the retro-cue paradigm to improve auditory short term memory representations' temporal precision, using AM sounds. This leads to our hypothesis: relative to uninformative retro-cues, the informative retro-cues will improve accuracy and response time, especially when detecting smaller changes in the probe's AM rate relative to its original AM rate. This was done by participants detecting changes in a sound's AM rate, utilizing two different sound types at varying AM rates. Our expectation with these AM rate differences is that participants would be near ceiling performance on the easier trials (± 20% of the original AM Rate) in both the informative and uninformative retro-cue conditions, so the retro-cue effect should be most substantial on the more difficult trials (±5% of the original AM Rates).

Methods and Materials

Participants

A total of 10 healthy young adults (5 men, 5 women, mean age = 23.8 years, SD age = 3.19 years) participated in this study. However, two participants were excluded from the data analyses due to failure to follow instructions or technical difficulties during the experiment, leaving 8 usable datasets. These participants were recruited through word of mouth as well as through SONA, where participants can sign up for lab studies for course credit or cash payment. Participants were compensated either 1.5 SONA credits or $20 for their time. The participants self-reported normal hearing and normal or corrected-to-normal vision and had no history of neurological disorders. Before beginning the experiment, participants provided written informed consent and filled out a general questionnaire involving their auditory and neurological history. The protocol was approved by the IRB at UC Merced.

Stimuli

The stimuli were comprised of a white noise sound and a 500 Hz pure tone generated through MATLAB at a sampling rate of 48,000 Hz. All stimuli lasted 500 ms. Custom MATLAB code was then used to apply amplitude modulation (AM) of varying rates to these white noise and pure tone stimuli. The original white noise sound is similar to radio static, while the AM white noise sounds sound like a rattling radio static. The original tone sound is similar to a phone beeping, while the AM tones sound as though the beeps are faster or slower. The original AM rate (either 10 Hz or 20 Hz) applied to the noise and the pure tone was counterbalanced across participants. For participants with an even subject ID number, the white noise's baseline AM rate was 20 Hz, and the pure tone's baseline AM rate was 10 Hz. For participants with an odd subject ID number, the white noise's baseline AM rate was 10 Hz and the pure tone's was 20 Hz. The probe sounds that participants could be tested on had AM rates of -20%, -10%, -5%, 5%, 10%, and 20%, relative to the original AM rate. Thus, for the baseline AM rate of 20 Hz, the possible probe stimuli had an AM rate of 16 Hz, 18 Hz, 19 Hz, 21 Hz, 22 Hz, and 24 Hz. For the baseline AM rate of 10 Hz, the possible probe stimuli had an AM rate of 8 Hz, 9 Hz, 9.5 Hz, 10.5 Hz, 11 Hz, and 12 Hz. The sounds with the negative AM rate percentages sound slower relative to baseline AM rate, while the positive AM rate percentages sound faster than the baseline sound. These AM rates were chosen to give the task some level of difficulty while remaining easy enough to keep participants engaged in the task. Using a range of AM rates for the probe stimulus also allowed us to look at the interaction between the task difficulty (i.e., larger AM rate differences such as ±20% should be easier to detect than smaller AM rate differences such as ±5%) and the retro-cue condition, in line with my hypothesis.

<u>*Task and Procedure:*</u>

An example of a trial is shown in Figure 1. The baseline sound waves for even participants as well as an example of the 24 Hz Noise sound (+20% Noise AM Rate) are depicted in Figure 1 as well. The study design used a retro-cue paradigm. The participant's task was to decide whether the probe sound was faster or slower than the related sound played at the beginning of the trial. Throughout each trial, except when the visual retro-cue was presented, the participants saw a fixation cross at the center of the screen. At the beginning of each trial two sounds played sequentially (i.e., Sound 1 and Sound 2). The participant was played the first sound, which was randomized to be a tone or a white noise sound. The Sound 1 stimulus played for 500ms. A 1000 ms pause, or inter-stimulus-interval (ISI), occurred then the Sound 2 stimulus played for 500 ms. If Sound 1 was the white noise, then Sound 2 was the tone and vice versa. After the two sequential sound stimuli were presented, there was a retention period of 1500 ms.

Following this retention period, the retro-cue appeared, (e.g., the N in the third box of Figure 1), which was a visual cue that appeared as a T, N, or X for 1000 ms. If the retro-cue was a T, then the participant should retroactively orient their attention to the memory representation of the tone sound that was played in order to perform correctly on the probe task. If the retro-cue was a N, then they should attend to the memory representation of the white noise sound that was played. Both the T and the N were informative retro-cues. Lastly, the letter "X" was used for the uninformative retro-cue condition. When the participant received the uninformative retro-cue, they should attend to the memory representations of both the tone and the white noise stimuli. After the retro-cue there was a brief pause of 1000 ms, giving the participant time to orient their attention to the retro-cued stimulus representation.

Finally, the probe sound played for 500 ms. The participant then provided an answer using the keyboard arrow keys to decide if the probe sound was faster or slower than the similar sound that was played at the beginning of the trial. The participant used the right arrow key if the probe stimulus was a faster AM rate than the original stimulus, and the left arrow key to respond that the probe stimulus was a slower AM rate than the original stimulus. The probe sound always matched the retro-cue. For example, if Sound 1 was a tone and the retro-cue was a T, then the probe sound that the participant was tested on was a tone.

Overall, there were 8 blocks with 48 trials per block and one practice block lasting 20 trials. During the practice block, participants were given feedback on their answers at the end of each trial to give them a better understanding of the task. Each block had 12 informative retro-cue trials for the tone, 12 informative retro-cue trials for the noise, and 24 uninformative trials. This was to keep the number of informative trials and uninformative trials at an equal number. During the regular blocks, participants were told by a message on the computer screen when a trial ended; this was to prevent participants from getting confused about what phase of a given trial they were currently listening to. Sound order, retro-cue condition, and the tested probe sounds were all counterbalanced through MATLAB. The task was given through using Presentation software (Neurobehavioral Systems, Inc., Berkely, CA). The stimuli were delivered to the participants through headphones. The participants completed the study in-person on the UC Merced campus.

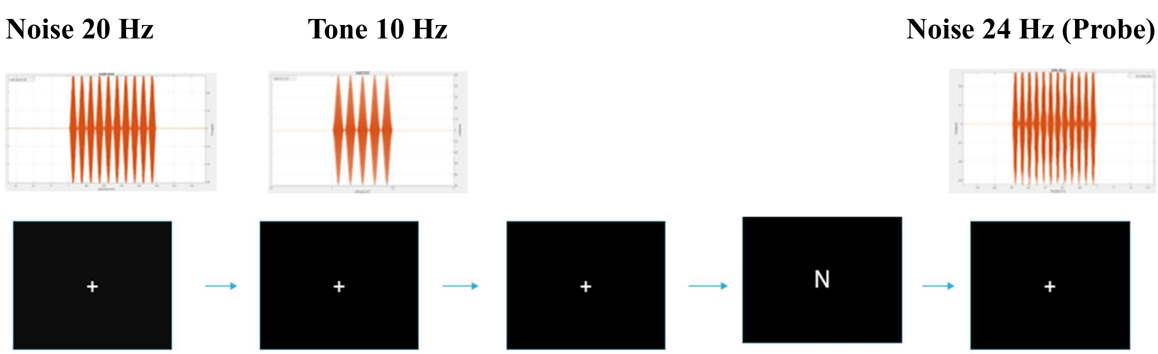

Figure 1: Trial Example with Sound Waves of Baseline AM Rates (for even participants) and +20% Noise AM Rate

Data and Statistical Analysis

The data were saved from the Presentation platform to logfiles (Neurobehavioral Systems, Inc., Berkely, CA). The logfiles were parsed through MATLAB (MathWorks, 2024) to create the tables that were read into RStudio. The data that were inputted into RStudio were single-trial data. The models I used for statistical analysis were evaluated in RStudio (RStudio Team, 2024) using the lme4 (Bates et al., 2015) and emmeans (Lenth, 2024) packages. All presented models had the Δ percent AM rate inputted as a signed value (e.g., +20% or -20%) and not as an absolute value (e.g., ±5% = 5%). Model 1 was a linear mixed effects model (lmer), in which the outcome variable was log-transformed response time (RT). This model includes the RT for all trials for every participant. The predictor variables were the retro-cue condition (RCCond) and the percentage of the Δ AM rate between the probe stimulus and its original AM rate (PercentAMRate) as well as their interaction. The Δ AM rate variable was initially treated as a continuous variable. The model also included random intercept by subject. The formula for model 1was: log(RT) ~ 1 + RCCond * PercentAMRate + (1 + | SubID), where SubID is the variable that that codes for each subject's ID number and RT is the response time of the participants for all trials. The retro-cue condition was converted into a categorical variable with three levels of 0 (Uninformative Cue), 1, (Informative Cue – Tone), and 2 (Informative Cue – Noise), with the reference level being set to 0 (Uninformative Cue).

Model 2 was a generalized linear mixed effect model (glmer), in which the outcome variable was accuracy. A glmer was used for accuracy due to it being a binary variable of 0 (incorrect response) or 1 (correct response). The formula for model 2 was: RespAcc ~ 1 + RCCond*PercentAMRate + (1 | SubID), where RespAcc is the participants accuracy on all trials. The other variables follow the same conventions as the previous model. Since there was a significant interaction between task difficulty (PercentAMRate) and the difference between uninformative retro-cues and informative-noise retro-cues (RCCond2 in Table 2) we decided to do a third model looking more closely at the effects of the different levels of amplitude modulation for the accuracy data.

Model 3 was also a generalized linear mixed effects model to predict accuracy. In Model 3 we factored the percent Δ AM rate, changing it from a continuous variable to a factor with six levels for the six AM rate differences. The reference level was the -20% amplitude modulated rate, and was compared with the -10%, -5%, 5%, 10%, and 20% rates. The formula for model 3 was: RespAcc ~ 1 + RCCond*CatAMRate + (1 | SubID), where CatAMRate is the factored variable of PercentAMRate used in model 2. The contrast function from the emmeans package (Lenth, 2024) was then used to provide p-values for the post-hoc comparisons between each pair of retro-cue conditions, separately for each percent AM level. The problem of multiple comparisons for these post-hoc comparisons was dealt with by using a Bonferroni correction.

Results

First, we examined whether the Retro-Cue condition and ΔAM Rate had any effect on the participants' log-transformed RT. Figure 2 shows the mean RTs for each ΔAM Rate for each retro-cue condition. The results of Model 1 (see Table 1) revealed significance on the intercept ($b = 7.11$, $p < 0.001$). A significant intercept indicates that the baseline log response time is different from 0 when all predictor variables are at their reference levels. However, we observed no significant fixed effects for the retro-cue conditions, ΔAM Rate, or their interaction.

Table 1: Model 1 Output (Predicting log-transformed RT)

```
Fixed effects:
                       Estimate Std. Error       df t value Pr(>|t|)    
(Intercept)             7.11292    0.07730  7.00083  92.020  4.7e-12 ***
RCCond1                -0.09298    0.04492  7.04447  -2.070   0.0770 .  
RCCond2                -0.09979    0.04496  7.05502  -2.219   0.0616 .  
PercentAMRate          -0.11042    0.15579  7.28551  -0.709   0.5005    
RCCond1:PercentAMRate   0.12005    0.15671 13.09930   0.766   0.4572    
RCCond2:PercentAMRate  -0.30194    0.15805 12.35845  -1.910   0.0795 .  
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
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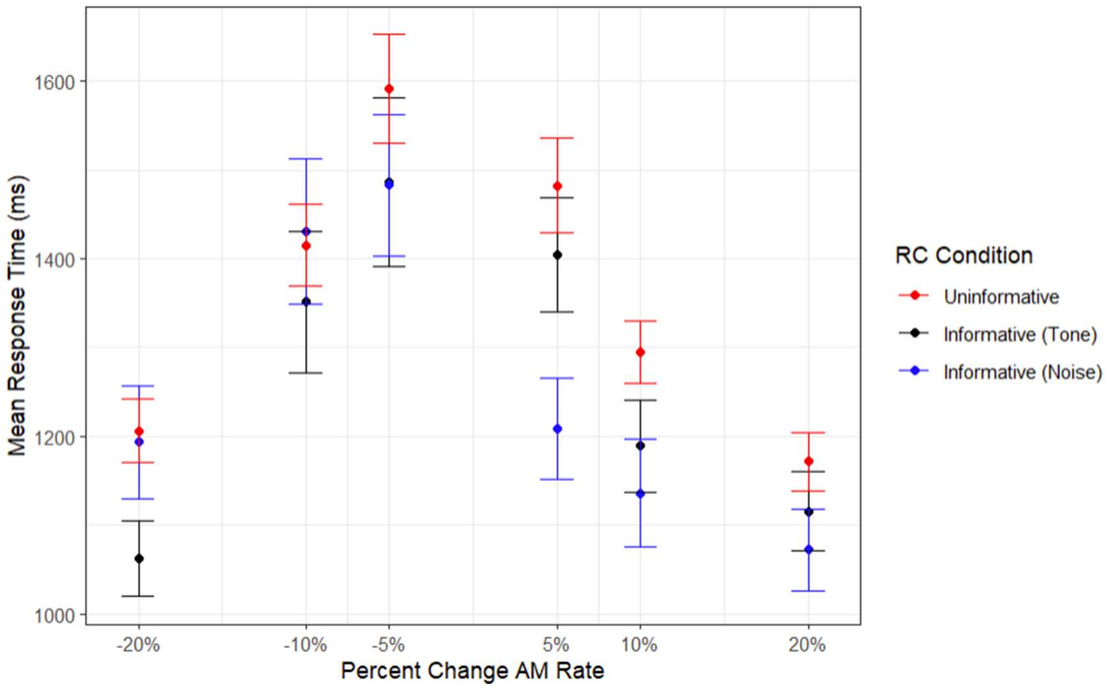

Figure 2: On the y axis we have mean response time and on the x axis we have the amplitude modulation rates. Separated by color we have the informative and uninformative retro-cue conditions. The dots represent the mean response time in milliseconds for each retro-cue condition at each ΔAM rate along with the error bars for each condition. The error bars represent the standard error of the mean.

Model 2 examined how the retro-cue condition and ΔAM Rate affected the participants' accuracy at determining whether the probe sound had a slower or faster AM rate than its original AM rate. Model 2 revealed statistical significance for the interaction of the informative-noise retro-cue and the variable of the percent amplitude modulation ($b = 3.88$, $p < 0.001$, See Table 2). Because of this significant interaction, we conducted further modeling and pairwise contrasts to understand what was driving the interaction—that is, at which ΔAM Rate levels were there differences between the three retro-cue conditions

Table 2: Model 2 Output (Predicting Accuracy with Percent AM Rate as a continuous variable)

Fixed effects:					
	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	1.74245	0.17765	9.808	< 2e-16	***
RCCond1	0.20042	0.12842	1.561	0.1186	
RCCond2	0.06781	0.12929	0.524	0.6000	
PercentAMRate	0.70024	0.53400	1.311	0.1898	
RCCond1:PercentAMRate	-1.68202	0.96965	-1.735	0.0828	.
RCCond2:PercentAMRate	3.88125	0.96969	4.003	6.27e-05	***

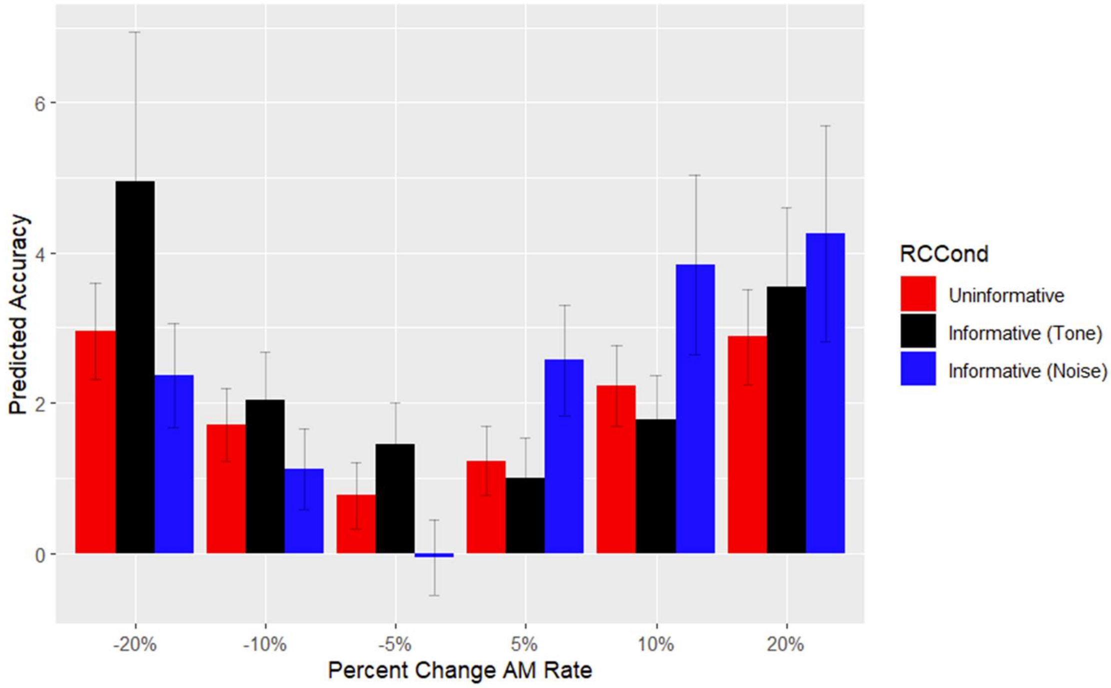

Figure 3: A bar graph looking at predicted accuracy on the y – axis, where the y-values are estimates based on the fitted model. The x-axis contains the 6 factored percent amplitude modulated rates, and the bars are separated into the 3 factored retro-cue conditions.

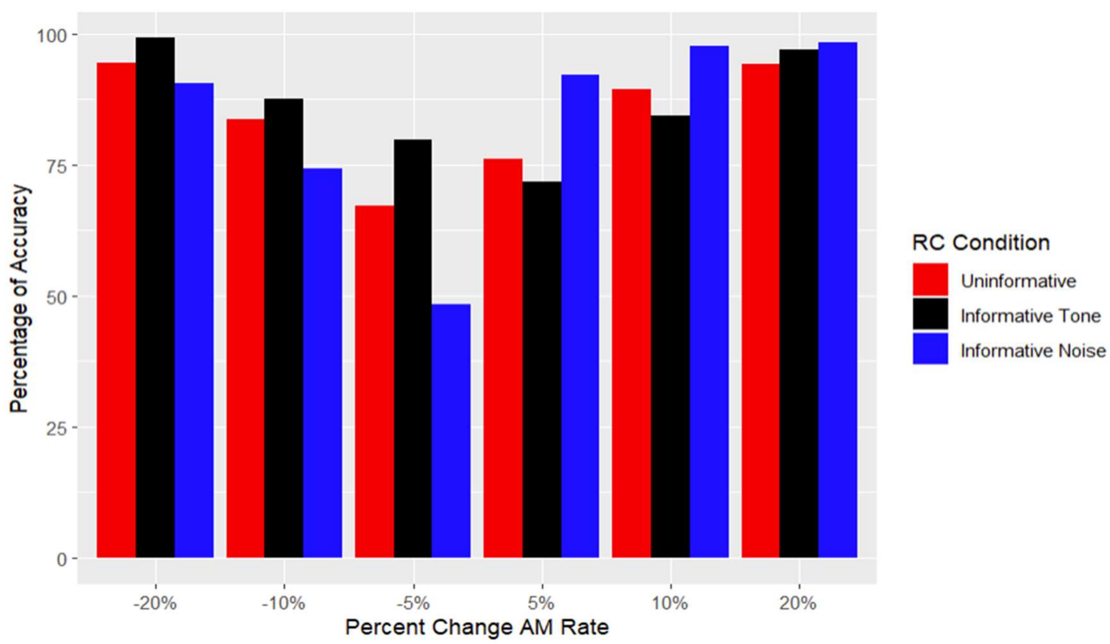

Figure 4: A bar graph looking at percentage of accuracy on the y – axis, where the y-values are the percentage of correct trials for all participants in each condition. The x-axis contains the 6 factored percent amplitude modulated rates, and the bars are separated into the 3 factored retro-cue conditions.

To further understand the interaction observed in Model 2, Model 3 used the factored variable of the ΔAM Rate. Table 3 shows the p-values when comparing the different levels of retro-cue conditions at each ΔAM Rate level. This revealed multiple instances of statistical significance with the values shown in Table 3**.** There was statistical significance found at the 5% AM rate between the informative retro-cue noise (RCCond2), and the uninformative retro-cue (RCCond0) ($b = 1.34$, $p = 0.004$). The positive estimate tells us that the informative noise retro-cue condition had significantly better accuracy than the uninformative retro-cue condition at the 5% AM rate. However, there were various other statistical significant findings shown in the table between the two informative retro-cue conditions, as well as one instance where the uninformative retro-cue condition had a statistically significant higher accuracy in the contrast when compared to the informative retro-cue noise condition at the -5% AM rate ($\beta = -0.8239$, $p < 0.01$).

Table 3: Results of the Pairwise Contrasts

CatAMRate	RCCond contrast	estimate	SE	df	z.ratio	p.value
-0.2	RCCond1 - RCCond0	2.003	1.03	Inf	1.944	0.933045
-0.2	RCCond2 - RCCond0	-0.5885	0.41	Inf	-1.435	1
-0.2	RCCond2 - RCCond1	-2.5915	1.04	Inf	-2.493	0.228123
-0.1	RCCond1 - RCCond0	0.3252	0.319	Inf	1.019	1
-0.1	RCCond2 - RCCond0	-0.5902	0.267	Inf	-2.207	0.492011
-0.1	RCCond2 - RCCond1	-0.9154	0.339	Inf	-2.699	0.125226
-0.05	RCCond1 - RCCond0	0.6768	0.261	Inf	2.59	0.172555
-0.05	RCCond2 - RCCond0	-0.8239	0.228	Inf	-3.616	0.005381
-0.05	RCCond2 - RCCond1	-1.5008	0.288	Inf	-5.202	3.55E-06
0.05	RCCond1 - RCCond0	-0.233	0.25	Inf	-0.932	1
0.05	RCCond2 - RCCond0	1.3376	0.363	Inf	3.685	0.004111
0.05	RCCond2 - RCCond1	1.5706	0.387	Inf	4.059	0.000888
0.1	RCCond1 - RCCond0	-0.4613	0.32	Inf	-1.441	1
0.1	RCCond2 - RCCond0	1.607	0.618	Inf	2.598	0.168608
0.1	RCCond2 - RCCond1	2.0684	0.633	Inf	3.265	0.0197
0.2	RCCond1 - RCCond0	0.6622	0.574	Inf	1.154	1
0.2	RCCond2 - RCCond0	1.3742	0.759	Inf	1.809	1
0.2	RCCond2 - RCCond1	0.712	0.874	Inf	0.814	1

Discussion

Using a retro-cue paradigm, we tested whether an informative retro-cue will improve accuracy and response time more significantly on the smaller changed amplitude modulations than an uninformative retro-cue. The current data for response time and accuracy does not support either prediction. However, one limiting factor here is the small sample size. If this project is revisited and a larger sample size is obtained, then it is possible that the informative retro-cue for both the noise and the tone stimuli will show significant improvements for both the accuracy and the response time when compared to the uninformative retro-cue condition at smaller ΔAM rates. This was shown with the smaller mean response times on the -5% and 5% on Figure 2. We found that the informative retro-cue noise condition significantly boosted accuracy at the 5% AM difference rate. From Figure 3, on the informative-tone trials, participants have higher accuracy on slower trials (-AM Rate) and lower accuracy on faster trials (+AM Rate), indicating that there may be some sort of response bias to respond “Slower” on the informative-tone trials and “Faster” on the informative-noise trials (since participants had higher accuracy on the “Faster” trials and lower accuracy on the “Slower” trials for the informative-noise retro-cue trials). This could be due to the sound types that were used (i.e., the white noise and tone). Most participants reported after the study that they felt one of the sound types were easier to detect the differences in. These reports were varied, non-descriptive, and not reported by every participant so the exact information cannot be provided, but these detection sensitivities to the different sound types could explain the differences in accuracy. There is also a possibility that the ΔAM rates is a sound feature that cannot be enhanced by orienting attention to the auditory memory representation. However, I am unable to report on significant generalizable effects at this time due to the small sample size and the mixed results of significance shown in Table 3. Recruiting more participants will hopefully lead to a more observable effect.

Lastly, we were unable to replicate the findings in Lim et al. (2015). The data did not lead to clear significant differences between the uninformative retro-cue conditions and informative retro-cue conditions, showing that a visual retro-cue can significantly enhance a specific feature of an auditory memory representation. However, there are still more questions to pursue in this avenue of research, and data supporting reasoning to return to the project while addressing the limitations we faced. One of my follow up questions would be “What separates the processing and storage of concurrent sounds vs sequential sounds?” This line of research is of value to the cognitive science community in discovering the role that attention plays in enhancing our short-term auditory memory representations. For example, determining which sound features can be enhanced with attention, could reveal a deeper understanding of how these auditory representations are encoded, and the effects that attention has on auditory short-term memory in our everyday lives.

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