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# The Cognitive Advantage of Percussive Auditory Information

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**The Cognitive Advantage of Percussive Auditory Information**

A thesis submitted in partial fulfillment of the requirement
for the degree of Bachelors of Science in Neuroscience from
The College of William and Mary

by

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Accepted for · Honors

(Honors)

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Williamsburg, VA
**May 6, 2009**

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The Cognitive Advantage of Percussive Auditory Information

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Acknowledgements

Abstract

Can a small change in the parameter of a to-be-remembered tone sequence affect how likely it is that a listener will recall it later? Naturally occurring amplitude envelopes (the intensity of a sound over time) have been shown to facilitate memorization of a series of tones better than computer-generated, flat envelopes (Schutz, Stefanucci, Carberry & Roth, 2009). Specifically, tone sequences with percussive tone envelopes (those that have a short attack and an exponential decay) are learned faster than those with flat tone envelopes (tones with no attack or decay, only a static onset and offset of the amplitude), even though both sets of tone sequences are easily recognized.  However, when participants are given equal exposure to either a set of percussive tones or flat tones, those who learn with percussive tones recall significantly more sequences than those who learn with flat tones. The experiments in this thesis replicated the effect found in Schutz et al. (2009) and suggest that the cognitive advantage of percussive amplitude envelopes does not have a specific locus (e.g. encoding or retrieval), but rather stems from information inherent to the tones themselves, and that this is effect is due to the ecological validity of percussive tones.

The Cognitive Advantage of Percussive Auditory Information

It comes as no surprise that our various sensory modalities yield information that is critical to navigating through our environment and guiding decisions about our actions in the environment. Although we tend to rely heavily on vision, audition also provides information-rich stimuli that are important in environmental navigation and action decision. Auditory information is so rich that the blind population, who have a much greater dependence on audition, have an incidence of 1 in 2 people with perfect pitch, while in the general population, this incidence is only 1 in 10 (Sacks, 2008). A small portion of these auditory cues can develop a meaning for the listener if they are encountered with frequency or are particularly relevant for one reason or another. The sound of a car getting louder over the course of a few seconds is an obvious signal that would prompt the listener to look for the oncoming car and get out of the way. There are other less dangerous sound-object associations as well, like the sound of a friend's voice and the image of their face or the sound of a loud, repetitious blaring with a fire alarm.

These sound-object associations seem to occur frequently in relation to human-computer interfaces. For example, a particular cell phone ring might indicate a received text message or a phone call. Likewise, an alarm may be used as a reminder for a particular task or event, and certain sounds can indicate successful or unsuccessful computer program use. These interfaces almost exclusively use static sounds, which have a flat amplitude envelope. An amplitude envelope can be defined as the feature of the sound that illustrates the change in amplitude of the sound over time. A flat amplitude envelope has a sudden onset, an unvarying steady state, and then a sudden offset (see Figure 1a). Many psychology studies that test auditory perception also use flat amplitude envelope tones. Given that flat amplitude envelopes do not occur naturally,

could these interfaces and experiments be improved or different if the tone envelope reflected

qualities of naturally occurring tones instead?

In addition to the artificial quality of flat amplitude envelopes, they may also strain the

perceptual system is such a way that is detrimental to their effectiveness. Attention is required to

perceive details in the abundance of information available in our environment. When a

participant is asked to attend to sounds in a noisy environment, functional magnetic resonance

images (fMRI) show increased activity in the auditory cortex (Tzourio, Massiouli, Crivello,

Joliot, Renault & Mazoyer, 1997). Furthermore, improper attention may be detrimental for

memory (Jenkins & Postman, 1948). The shape of a flat amplitude envelope does not allow the

listener to predict features of the sound because the invariant steady state makes it impossible to

establish any sense of sound duration or source. Thus, sounds that have flat amplitude envelopes

may require more attention to process.

Not all man-made sounds, however, are hard to process. Some man-made sounds, like

those produced by string and horn instruments, have a rectangular shaped amplitude envelope,

similar to that of flat amplitude envelopes. However, their amplitude state fluctuates over time

and their offset is more gradual. These man-made sounds, therefore, obey the natural physics of

sound, whereas flat amplitude envelopes do not. Other man-made sounds, like those produced by

two objects colliding in space, are generally described as having a percussive amplitude

envelope, which has a strong attack followed by an exponential dissipation of sound (see Figure

1b). Percussive tones are usually produced by the collision of any two objects, the impact of

which results in a quick attack, and the rate of decay of the sound waves provides information

about the materials involved in the collision. In using percussive amplitude envelopes for human-

computer interfaces, the user is easily able to predict sound duration and cause, and some of the

additional attention needed to process flat amplitude envelopes can be reduced.
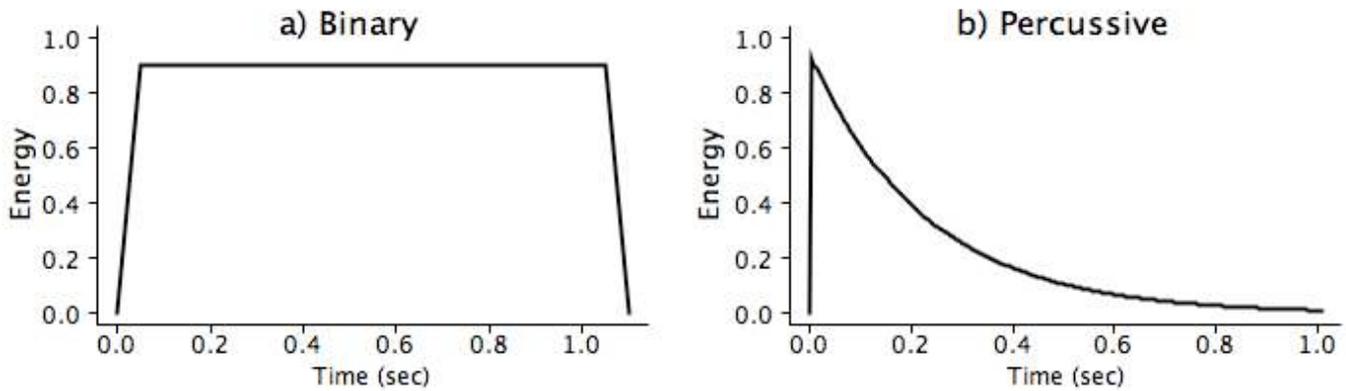


**Figure 1.** Flat and Percussive Amplitude Envelopes. Flat tones (left) have a sudden onset, unvarying steady state and a sudden offset. Percussive tones (right) have a rapid attack followed by a gradually declining offset.

Percussive envelopes may take fewer attentional resources to process, and recent work by

Schutz, Stefanucci, Carberry and Roth (2009) shows that people are willing to pay more for

interfaces that include these sounds. They found that listeners offered to pay $5.25 more, on

average, for a cell phone that had a ring tone using a percussive envelope in comparison to a

phone with a flat envelope ring tone. Furthermore, this increased monetary value may also

translate into increased cognitive value. High fidelity audio has been shown to significantly

improve memory performance of recalled objects in a virtual environment, both in increased

number of correct object-room associations and decreased number of inappropriate object-room

associations (Davis, Scott, Pair, Hodges & Oliverio, 1999). These findings suggest that audio

quality can enhance cognitive processes, in addition to affecting likeability. Moreover,

participants in the Davis et al. (1999) study reported that the addition of sound increased the

sense of "being there" in the virtual world. This idea of "being there" may be the best way to

describe, in words, that the participants had a more natural, realistic sensory experience when high-quality audio was present. These more natural, familiar experiences may contribute to higher cognitive performance.

Within the context of the entire temporal envelope, it seems as though the onset in particular could be of great importance for cognitive processing. If the initial 50 milliseconds of a tone are altered, it is possible to confuse the listener, such that he or she will attribute the sound to a different instrument than the one that actually produced the tone (Grey & Gordon, 1978). This confusion may be due to the fact that varying the characteristics of temporal envelopes at the onset of a sound has been shown to modify the response latency and response magnitude of auditory neurons (Heil, 2003). Developmental dyslexia may be a symptom of an inability to perceptually discern amplitude envelope onsets, accounting for 25% of the variance in reading and spelling acquisition in dyslexic and normally reading children (Goswami, Thomson, Richardson, Stainthorp, Hughes & Scott, 2002). Single cell recordings in the auditory cortex of cats show that spectral and auditory transients[1] are encoded with both different cell types and different codes (Sakai, Chimoto, Qin & Sato, 2009). The cells that primarily code auditory transients could preferentially encode percussive tones better than flat tones because the unvarying steady state of the flat tone confuses the neurons that code for transience in the tones.

These anatomic and physiological differences in encoding different attributes of a sound are not only seen at the onset of a sound, but throughout its duration. Studies indicate that neurons are able to decipher temporal information into transient and sustained patterns via separate areas of the auditory cortex (Seifritz, Esposito, Hennel, Mustovic, Neuhoff, Bilecen, Tedeschi, Schleffler & Salle, 2002). A study with rhesus monkeys showed that auditory spatial

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[1] Auditory transients are defined as a sudden increase in sound output. Sakai et al. (2009) defined auditory transients as the stimulus onset.

and pattern information is processed through separate and specialized streams in the caudal belt and anterior belt, respectively, of the auditory cortex (Tian, Reser, Durham, Kustov & Rauschecker, 2001). This research shows that there is a neural basis for the perceptual discernment of amplitude envelopes.

Flat and percussive tone envelopes can show variations in stimulus intensity in a matter of milliseconds. If the perceptual system can detect this very small change in auditory information (when spectral or frequency information is identical), then auditory neurons may also encode information at this order of magnitude, which could contribute to changes in memory representations. Yang, DeWeese, Otazu & Zador (2008) showed that rats are able to use inter-cortical differences in stimulation, at an interval as small as 3 milliseconds, to guide decisions (specifically, attain above chance performance in a two-alternative-choice task). If extremely minute differences in timing are able to affect decision making, it follows that it may be possible that timing, or the shape of the envelope, can affect memory or memory representations as well, another higher-order cognitive process.

In musical terms, the shape of the amplitude envelope normally refers to the construct known as timbre. The timbre of a sound tends to have various definitions, but is understood to be the vague quality of a sound that allows a listener to distinguish sounds that have the same frequency and loudness but have differences in their attack and decay, vibrato and harmonic content. For example, when a bell and a piano both play a middle C, the difference is heard without fail. Reversing the amplitude envelope of a sound can render it unrecognizable from the original source (Paquette & Peretz, 1997). Previous research has shown that changes in timbre have the potential to affect performance on an object-association memory task (Schutz, Stefanucci, Carberry & Roth, 2009). This study adds to mounting evidence that suggests that

perceptual differences in sounds can differentially affect the higher-order processes that use this perceptual information. Specifically, Schutz et al. found that participants required significantly fewer training blocks to learn ten object-tone sequence associations (to a 70% threshold) when the tones had a percussive amplitude envelope. In a second experiment where all participants were given only one training block, participants who were presented with percussive tone sequences remembered more associations than those participants who had flat amplitude envelopes. Both experiments also showed that only recall was affected, while correct recognition of tone sequences (correctly identifying that a tone sequence was present in the training block) was similar across the two conditions. This suggests that participants were equally able to become familiar with either type of tone, but did not show equal abilities in associating the sequences with the proper objects.

*Overview of Current Studies*

The current studies examined whether the cognitive benefits observed in the previous studies on amplitude envelope and memory (Schutz et al., 2009) could be localized to either encoding or retrieval processes and if the ecological validity of percussive amplitude envelopes is at the root of the effect. In a number of studies, memory has been to rely, in part, on context. Non-item related cues like location (Godden & Baddeley, 1975), and background music (Balch, Bowman & Mohler, 1992; Smith, 1985) have been shown to improve memory if these cues are present at both training and testing. Even mild alcohol and nicotine intake can significantly improve recall compared to control subjects if alcohol and nicotine were present for both conditions during the study session (Lowe, 1988). Specific effects of cue dependency have been found often by using experimental designs that compare matched and mismatched cues at

encoding and retrieval. For example, Dodson & Shimamura (2000) compared word recognition when the test words were spoken either with the same voice or with a different but familiar voice than the training words. This resulted in matched and mismatched conditions at encoding and retrieval, respectively, which were used to examine the effect of cue availability on source memory. Correct source recognition was higher for the matched condition than the mismatched condition. Three-month old infants were able to remember two musical pieces for twenty-four hours after training even when training and testing music was mismatched, but up to seven days retention was seen if the music for the training and testing sessions was matched (Fagen, Prigot, Carroll, Pioli, Stein & Franco, 1997). Using training and testing mismatched paradigms has revealed that contextual cues related to environment, pharmacological state and the to-be-remembered items themselves help aid memory retention.

Previous research has shown that tone envelope can influence the recall of object-tone associations (Schutz et al., 2009). Data from this study showed that these associations were learned faster when percussive tone sequences were used, possibly suggesting differential processing at information encoding. Therefore, we hypothesized that the amplitude envelope influenced learning and recall because of the perceptual differences in the percussive and flat tones that were present at encoding.  It is also possible that the amplitude envelope differentially influenced processing at retrieval, which our mismatched experimental design would also be able to reveal. In the following two experiments, I demonstrate that these differences in perception are consequential for cognitive performance (as shown in the Schutz et al. study) and reliable, and that the locus of the effect is not reducible to encoding or retrieval but rather to the perceptual information contained in the tones. Experiment 2 suggests that the ecologically validity of percussive amplitude envelopes has a high contribution to its cognitive advantage.

<u>Experiment 1</u>

In this experiment, participants were placed in one of four conditions: (1) learning and testing with percussive tone envelopes, (2) learning and testing with flat envelopes, (3) learning with percussive envelopes, but testing with flat envelopes, or (4) learning with flat envelopes, but testing with percussive envelopes.  Recognition memory was tested via an adapted old-new paradigm (Mandler, 1980; Tulving, 1985). Recall memory was tested with a paired-associates paradigm.

**Method**

*Participants*. Eighty (31 male, 49 female) College of William and Mary undergraduate students participated for either introductory psychology course credit or $5 payment.

*Stimuli & Apparatus*. Participants sat at a small table with ten household objects (a laser distance meter, a Blockbuster membership card, a cell phone, a set of keys, a camera, an alarm clock, a remote control, a calculator, a jewelry box and a CD case) arranged in two rows of five objects (see Figure 2). Creative Inspire 290 PC multimedia speakers were placed approximately 2 feet away from the participant. Sound was controlled by the experimenter, who sat at a desktop computer 5 feet away from the participant. A filing cabinet between the desk and small table served to block the participant from viewing anything done by the experimenter on the computer. Participants were trained on the memory task with only the type and order of tone sequences differing between conditions.

Twenty distinctive tone sequences were created and assembled using the open-source sound generation program SuperCollider[2] from a master set of thirteen tones arranged

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[2] http://supercollider.sourceforge.net/

chromatically from A2 (220 Hertz) to A3 (440 Hertz). The tone sequences consisted of four

tones each. Two versions of each sequence were put together with the open-source sound

recording and editing program Audacity[3]. This created a total of forty tone sequences, twenty of

each amplitude envelope being used. Both tone envelope groups had tone sequences labeled 1-

20, which matched in frequency, pattern and loudness to their counterparts in the other tone

envelope set, respectively (e.g. percussive sequence 4 matched flat sequence 4, etc.). The

training block contained either sequences 1-10 (set A) or 11-20 (set B) of either the percussive

tone or flat tone type. Participants were tested using all tones (1-20) from the appropriate group.

     *Procedure*. The order and arrangement of objects on the table was the same for each

participant; but for each participant the objects were randomly paired with tone sequences. The

experiment was described to the participant in full, including the structure of the training session,

the distracter task between training and testing sessions, and that a test session would follow the

break.



**Figure 2.** Experimental Setup. Participants sat down at a table with two rows of five everyday
objects placed in front of them.

     Participants were randomly assigned to one of four conditions (n = 20). In the first

condition, participants were both trained and tested with the percussive tone sequences, referred

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[3] http://audacity.sourceforge.net/

to as the percussive/percussive condition. In the second condition, participants were trained and tested with the flat tone sequences (flat/flat). In the third and fourth conditions, participants were trained with the percussive tone sequences and tested with the flat tone sequences or vice versa (percussive/flat and flat/percussive, respectively). The sequence-object associations were determined prior to the participant's arrival and the order of sequences was derived from a random number table such that all associations were arbitrary and each tone sequence had an equal chance to be paired with any of the objects. The entire procedure lasted approximately 30 minutes.

**Training:** Each participant was told that they would hear a series of tone sequences and that they were to associate each of these tone sequences with one of the objects in front of them. They were told that the tone sequence would be played three times and that they were allowed to touch, feel or manipulate the object in any way during this time in order to aid retention of the association between the tone sequence and the object. The experimenter then went through all ten object-sequence pairs in this fashion.

**Break:** After the training session the experimenter loaded two standard computer games (Minesweeper and Solitaire) on a desktop computer. Participants were told that they could play the games for five to ten minutes, during which time the experimenter left the room. Seven minutes later the experimenter returned. The break served as a distracter task in order to prevent rehearsal of the tone sequences as well as to give time for the associations to be transferred out of working memory and into short-term memory.

**Test:** The structure of the memory test was explained to the participants after the break. Specifically, they were told that the experimenter would play a set of 20 tone sequences, some of which were heard during the training block, and some which were new to the participant.

Participants were told that each tone sequence would be played only once. For one half of the participants in each condition, set A (tones 1-10) served as the training sequences and were therefore "old", while set B (tones 11-20) served as the new sequences. For the other half of participants, the opposite was true. After each tone sequence was played, participants were asked to identify if the tone sequence was "old" (heard during the training block) or "new" (not heard during the training block). They were also asked for a confidence rating for that judgment ranging from one to six, with one being "not at all confident" and six being "very confident". If the participant indicated that they thought the tone sequence was old, then they were asked with which object they believed the sequence was associated. Participants were forced to make a choice even if they felt uncertain. A second confidence rating with the same 1-6 scale was also recorded for this judgment. Participants were allowed to answer "old" for an unlimited number of sequences and were also able to "re-guess" an object that they had already reported was paired with a previous sequence, but they were not allowed to change previous answers. Recognition and recall of the entire set of twenty test sequences were tested using this procedure. No feedback was given to the participant during the testing phase.

A small survey was given following the completion of the test. This survey asked for previous musical experience, likeability of the tones and any strategy that the participant may have used to memorize the sequence-object associations. The participant was then debriefed in full and given the opportunity to ask questions about the procedure and hypothesis of the experiment.

**Results**

*Recognition and Recall*. A multivariate analysis of variance (MANOVA) was performed with accurate recognition (correctly identifying an old sequence as old) and accurate recall (correctly connecting an old sequence and the object with which it was associated) as dependent variables and condition as the independent variable. Condition did not affect recognition ability of old sequences (percussive/percussive $M = 7.60$, $SD = 1.54$; flat/flat $M = 7.45$, $SD = 1.67$; percussive/flat $M = 7.30$, $SD = 1.38$; flat/percussive $M = 6.80$, $SD = 1.47$), $F(3, 76) = 1.05$, $p = 0.38$, $\eta_p^2 = 0.04$. This is important because it shows that even in the mismatched conditions, participants were still able to remember and translate frequency and pattern to different amplitude envelopes. However, condition did significantly affect recall, $F(3, 76) = 2.91$, $p = 0.04$, $\eta_p^2 = 0.10$ (see Figures 3 and 4, respectively). Post-hoc analysis using Fisher's LSD showed that participants who had percussive tone sequences during training and testing correctly recalled significantly more pairs ($M = 3.90$, $SD = 2.22$) than participants in all three other conditions (flat/flat $M = 2.85$, $SD = 1.66$, $p = 0.05$; percussive/flat $M = 2.65$, $SD = 1.50$, $p = 0.02$; flat/percussive $M = 2.45$, $SD = 1.23$, $p = 0.01$). No other significant differences were present between the groups.
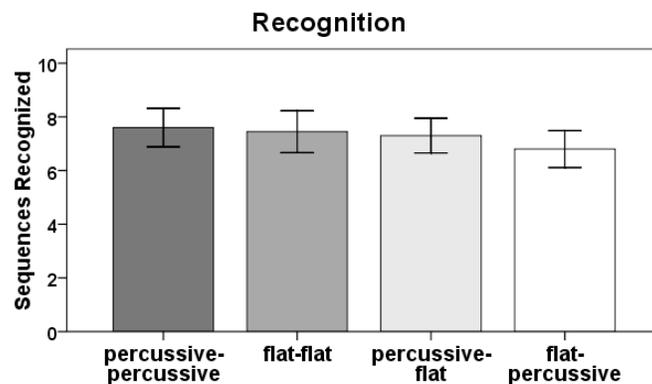
**Figure 3.** Average number of sequences correctly identified as "old" during the training block, by condition. Bars mark a 95% confidence interval.
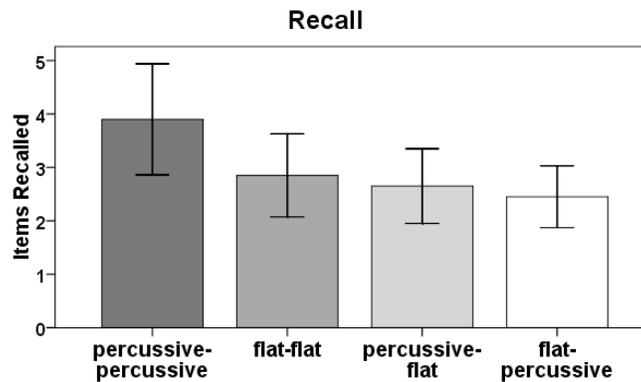


**Figure 4.** Average number of items associated with the correct tone sequence during the testing block, by condition. Bars mark a 95% confidence interval.

*False Alarms*. If a participant indicated that a sequence was old when it was not (e.g., they falsely believed they had heard the sequence during the training block), this was marked as a false alarm (Underwood, 1965). An analysis of false alarms also revealed a significant effect of condition, $F(3, 76) = 4.58, p = 0.005, \eta_p^2 = 0.15$ (see Figure 5). Fisher's LSD post-hoc analyses revealed that the percussive/percussive condition ($M = 2.00, SD = 1.52$) had significantly fewer false alarms than all three other conditions (flat/flat $M = 3.20, SD = 1.80, p = 0.02$; percussive/flat $M = 3.55, SD = 1.10, p = 0.002$; flat/percussive $M = 3.60, SD = 1.73, p = 0.002$). No other differences were significant. This may indicate that participants in the percussive/percussive condition not only learned the correct sequences better, but they also had an increased ability to discern and reject incorrect sequences. Both capabilities are required for accurate memory.
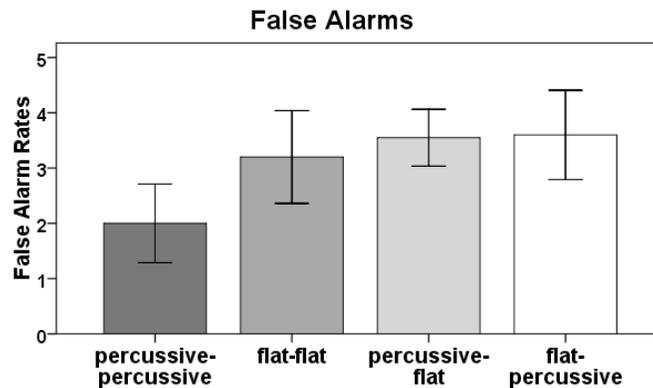
**Figure 5.** False alarm rates by condition. The percussive-percussive condition had significantly fewer false alarms, in addition to higher recall performance, than the other three conditions. Bars represent 95% confidence intervals.

*Confidence Ratings.* Participants' confidence ratings were averaged for (1) correct recognition trials and (2) correct recall trials. Using a Pearson's two-tailed correlation, we found that confidence ratings were positively correlated with the number of correct trials for both recognition ($r = 0.28, p = 0.013$) and recall ($r = 0.43, p = 0.001$). Separate univariate ANOVAs revealed no differences in confidence levels for correct recognition (percussive-percussive $M = 4.40, SD = 0.83$; flat-flat $M = 4.17, SD = 0.85$; percussive-flat $M = 4.01, SD = 0.72$; flat-percussive $M = 3.86, SD = 1.04$) $F(3, 76) = 1.38, p = 0.25, \eta_p^2 = 0.05$ or correct recall (percussive/percussive $M = 3.90, SD = 1.15$; flat/flat $M = 3.97, SD = 1.49$; percussive/flat $M = 3.74, SD = 1.60$; flat/percussive $M = 3.69. SD = 1.15$) $F(3, 76) = 0.185, p = 0.91, \eta_p^2 = 0.01$ (see Figures 6 and 7, respectively).
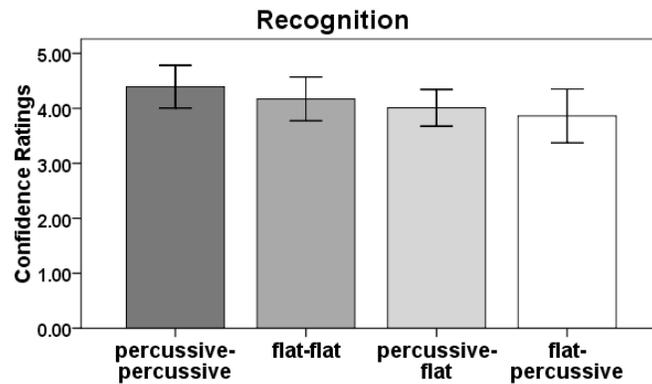
**Figure 6.** Confidence ratings for correct recognition judgments. No significant differences by condition were found. Bars represent 95% confidence intervals.
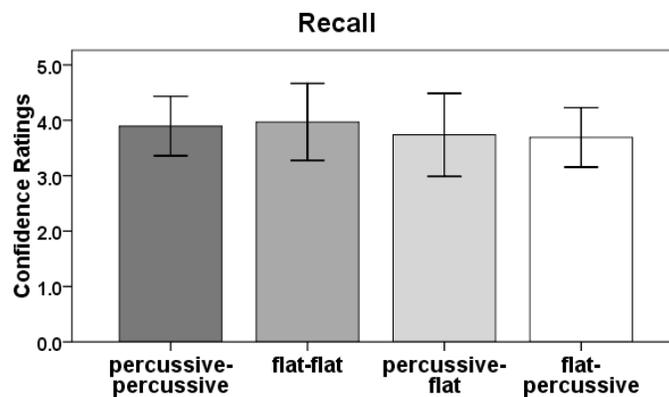


**Figure 7.** Confidence ratings for items correctly recalled. No significant differences by condition were found. Bars represent 95% confidence intervals.

Experiment 2

It is well known within memory research that the quality of stimulus processing has a predictable impact on the subsequent retention of that stimulus. Nairne & Pandeirada (2008), however, found that when words were processed by assessing their usefulness in a survival situation, consequent maintenance of information was significantly higher than even imagery or

self-referential techniques. Kang, McDermott & Cohen (2008) replicated this effect even when an additional control group, who processed words based on their relevance to executing a bank robbery, was added to match the arousal level and novelty of processing words in the context of survival. This suggests that fitness-relevant information is preferentially remembered over other information. If this is the case, then naturally occurring percussive sounds may have a much greater chance of being remembered better given their fitness relevance as compared to their man made, flat tone counterparts.

The aforementioned studies suggest that ecologically valid information has an advantage over other to-be-remembered information. In order to test that theory in relation to our study, we introduced a new amplitude envelope, which will be referred to as percussive-backward because it is the reverse envelope of the percussive tones. Specifically, it is characterized by a gradual, exponentially rising onset and a sharp, sudden offset. If ecological validity is why percussive tone sequences are advantageous for recall, then it will maintain this advantage when tested against other non-natural tones.

## Method

*Participants*. Twenty-two (8 male, 14 female) College of William and Mary undergraduate students participated for introductory psychology course credit.

*Stimuli & Apparatus*. The same objects and percussive tone sequences from Experiment 1 were used in this experiment, including the set up of the objects and random, predetermined sequence-object associations. A second set of 20 sequences was created in the same manner as these tones but with the percussive-backward amplitude envelope.

Procedure. The procedure for this experiment was exactly the same as in Experiment 1, but there were only two conditions and both conditions had matched amplitude envelopes at training and testing. The participants were randomly assigned to either the percussive-forward or percussive-backward condition and were trained and tested with matched amplitude envelope sequences.

**Results**

*Recognition and Recall.* A multivariate analysis of variance (MANOVA) was performed with accurate recognition and accurate recall as dependent variables and condition as the independent variable in the same manner as Experiment 1. Once more, condition did not affect recognition ability of old sequences, although it trended towards significance (percussive-forward $M = 8.27$, $SD = 1.10$; percussive-backward $M = 7.45$, SD $= 1.04$), $F(1, 20) = 3.21$, $p = 0.09$. A significant difference was found in recall scores by condition. As hypothesized, participants who heard percussive-forward tones ($M = 4.18$, $SD = 1.54$) recalled significantly more sequence-object associations than those who heard percussive-backward tones ($M = 2.73$, $SD = 1.27$), $F(1, 20) = 5.85$, $p = 0.03$, $\eta_p^2 = 0.23$ (see Figures 8 and 9, respectively).
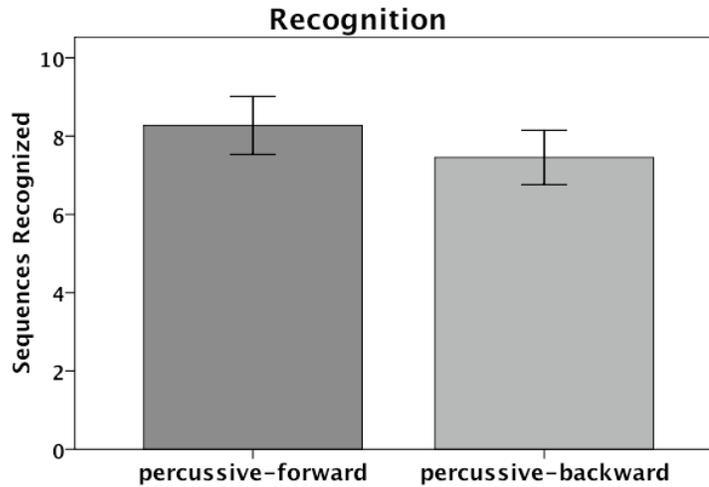
**Figure 8.** Average number of sequences correctly recognized by condition for Experiment 2. Bars represent 95% confidence intervals.
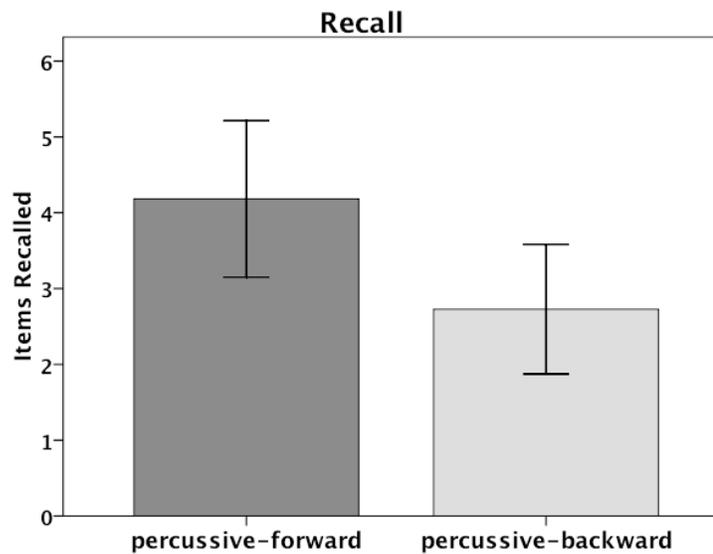


**Figure 9.** Average number of items correctly recalled by condition for Experiment 2. Bars represent 95% confidence intervals.

*False Alarms*. False alarms were recorded in the same manner as Experiment 1. We found a significant difference in false alarm rates by condition; again, participants who heard percussive-forward amplitude envelopes had fewer false alarms ($M = 1.82$, $SD = 1.40$) than

participants who learned with percussive-backward amplitude envelopes ($M = 3.00, SD = 1.18$),

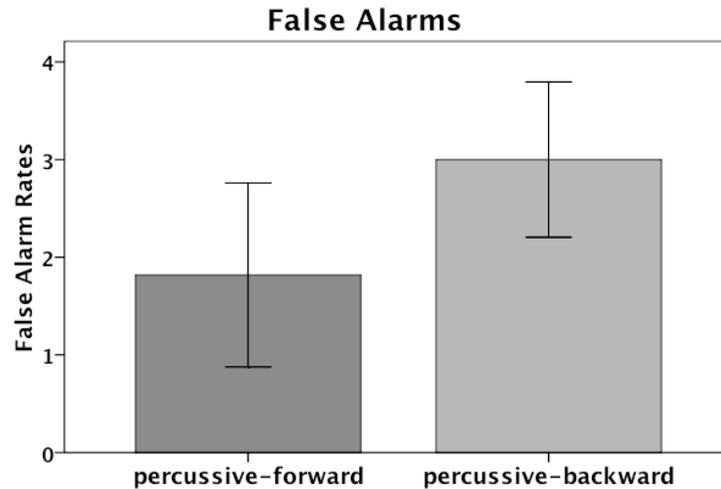$F(1, 20) = 4.57, p = 0.05, \eta_p^2 = 0.19$ (see Figure 10).



**Figure 10.** False alarm rates by condition for Experiment 2. Bars represent 95% confidence intervals.

*Confidence Ratings*. Confidence ratings were averaged in the same way as Experiment 1.

A Pearson's two-tailed correlation revealed that confidence ratings were again positively

correlated with the number of correct trials for both recognition, ($r = 0.53, p = 0.01$), and recall ($r$

$= 0.60, p = 0.01$). Separate univariate ANOVAs revealed higher confidence levels for correct

recognition (percussive-forward $M = 4.52, SD = 0.87$; percussive-backward $M = 3.77, SD =$

$0.61$), $F(1, 20) = 5.29, p = 0.03, \eta_p^2 = 0.21$, but not correct recall, although the difference trended

toward significance (percussive-forward $M = 4.12, SD = 0.85$; percussive-backward $M = 3.14$,

$SD = 1.35$), $F(1, 20) = 4.17, p = 0.055, \eta_p^2 = 0.17$ (see Figures 11 and 12, respectively).
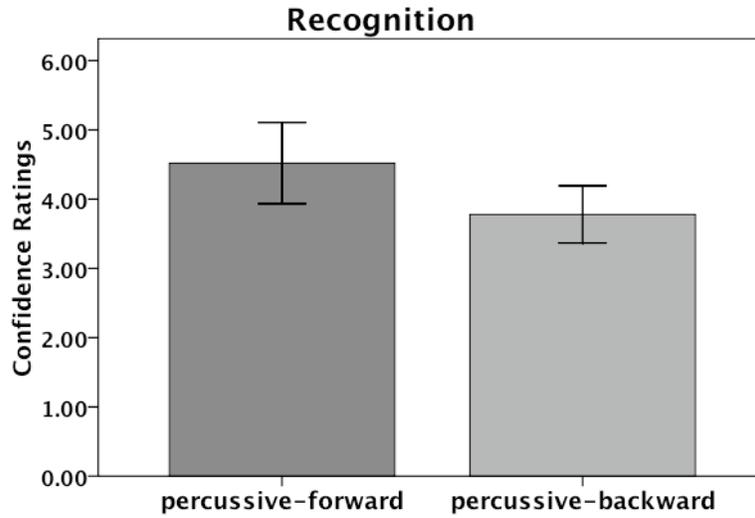
**Figure 11.** Confidence ratings for correct recognition of sequences by condition for Experiment 2. Bars represent 95% confidence intervals.
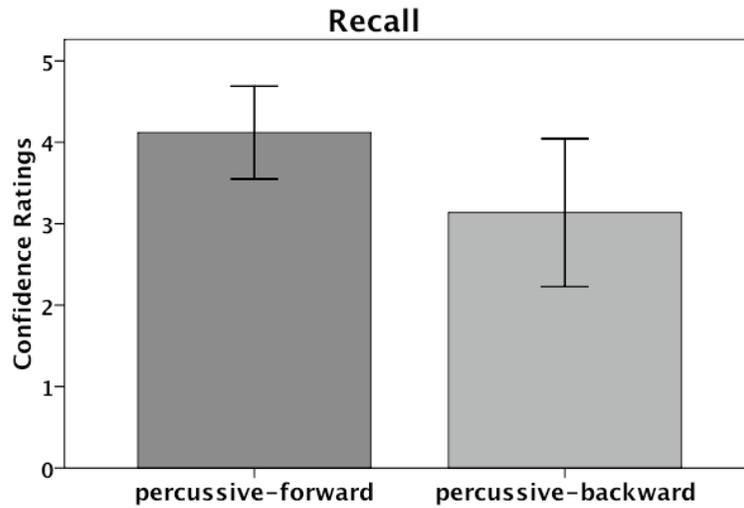


**Figure 12.** Confidence ratings for correct recall by condition for Experiment 2. Bars represent 95% confidence intervals.

**General Discussion**

The results of the experiments reported in this thesis replicated and extended the Schutz et al. (2009) findings.  The results of Experiment 1 suggest that percussive envelopes only provide cognitive benefits when they are present at both encoding and retrieval.  The results of Experiment 2 suggest that percussive envelopes only provide cognitive benefits when they are ecologically valid.

This finding supports previous research showing that matched conditions at encoding and retrieval often benefit memory processing (Lowe, 1988; Dodson & Shimamura, 2000; Fagen et al., 1997). However, the results of Experiment 1 also contribute to this body of literature because the matched flat envelopes at encoding and retrieval did not provide a memory advantage. A strategic technique known as the distinctiveness heuristic is described as the use of vivid and unique information to identify previously encountered stimuli and reject novel stimuli (Schacter, Israel & Racine, 1999). Distinctive information, such as pictorial encoding instead of word encoding, has been shown to reduce false alarm rates in memory recognition tests (Schacter, Cendan, Dodson & Clifford, 2001). The predictive features of percussive tones may also be another piece of distinctive information that increases accurate memory retention. A significant difference in false alarm rates in Experiment 1 was an unexpected effect that was not present in the Schutz et al. (2009) study, but may be described by the distinctiveness heuristic. The ability to reject false stimuli is one facet of accurate information retention because it requires the listener to establish characteristics of the sound that will allow them to discern between familiar and novel sounds.

Furthermore, in Experiment 1, we found that the memory advantage was specific to recall tests only.  Averages for the memory recognition test were nearly identical across the four

conditions.  This suggests that the type of envelope does not differentially influence the ability to recognize the sequences of tones.  This finding is important in that it confirms that differences in learning across conditions were not the potential cause of the recall effect.  Furthermore, because recall averages were not significantly different among the matched, flat condition and both mismatched conditions, it seems reasonable to suggest that the lower recall scores in the mismatched conditions were not due to any confusion or an inability to transfer the frequency patterns from one envelope to another. Both mismatched conditions did as poorly as the matched, flat envelope condition, suggesting that the memory advantage for recall in the percussive, matched condition could have occurred at either encoding or retrieval or both.

We were therefore unable to localize this effect of percussive envelopes on recall to memory encoding or retrieval, suggesting that this effect is a feature of the information inherent to the amplitude envelopes. However, this conclusion is certainly open to interpretation.  One interesting consequence of this proposal is that, contrary to other memory experiments (Godden & Baddeley, 1975; Lowe, 1988; Dodson & Shimamura, 2000; Fagen et al., 1997), matched information alone was not enough to improve object recall. Again, if recall were only based on cue dependency, participants in the matched, flat condition would have done better than the two mismatched conditions.

The results of Experiment 2 of this thesis provided additional insights about why certain differences in timbre have an effect on the ability to make arbitrary sound-object associations. Given that the findings of Experiment 1 suggested that it was something inherent to percussive tones that contribute to the memory advantage, we tested whether tones that had the same information as the percussive tones in Experiment 1, but in reverse order, would also produce memory advantages. We found that although both sets of tones are easily recognized,

participants who learned with percussive-forward tones once again had higher recall scores. Jenkins and Postman (1948) found that improper attention could have a negative impact on learning. Flat tones and percussive-backward tones are evolutionarily novel, and therefore may be distracting, diverting attention away for important aspects of the stimulus. The onset of an amplitude envelope has been shown to be of particular importance for source recognition and neural encoding (Grey & Gordon, 1978; Heil, 2003; Sakai et al., 2009) and syllable discrimination (Goswami et al., 2009). Percussive-backward tones have no distinguishable onset, which could be difficult for the perceptual system to handle, translating into deficits in any process that uses this perceptual information. It is also important to note that, unlike Experiment 1, both types of sounds in Experiment 2 had the same average intensity only in reverse (spectral or frequency information was identical), showing that intensity itself was not affecting recall, but rather the timing of the intensity.

Experiment 2 also revealed a significant difference in false alarm rates by condition. As in Experiment 1, we believe that this may be due to the distinctive but not distracting information contained in the percussive-forward amplitude envelope. Participants' confidence ratings for both recognition and recall were positively correlated in Experiment 1 and Experiment 2, showing that participants generally had an accurate sense of their performance as well.

If this effect is due to information inherent to the signal, there must be some difference in how the information is processed that contributes to its advantage. Some research has demonstrated a neural basis for temporal envelope discrimination in the auditory cortex (Seifritz et al., 2009; Tian et al., 2001). It is possible that this difference in discrimination causes the percussive envelopes to be differentially processed in the auditory cortex. In a comparison with normal hearing and hearing impaired participants, however, Füllgrabe et al. (2003) found that

cochlear damage had no effect on recognition of temporal envelopes, which seems to be indicative of a neural structure that is farther along the multistep process of analyzing incoming auditory stimuli than the initial wave energy to electric signal transduction.

Further studies may be able to benefit from the use of functional imaging techniques to compare behavioral responses during the testing session. One previous study attempted to localize recognition by subtracting PET images taken while listening to new auditory sentences from old, learned sentences (Tulving, Kapur, Markowitsch, Craik, Habib & Houle, 1994). They found increases in blood flow primarily in the cortical sulci. A similar technique could be used to compare sequences learned with percussive envelopes, but tested with either percussive or flat sequences. Both correct recognition and recall as well as false alarms could be calculated and correlated with blood flow changes in various auditory and memory areas of the brain. Furthermore, it would be interesting to discern whether areas that were implicated at encoding (like the hippocampus) could be differentially active for percussive or flat envelopes.  As Davachi and Wagner (2002) have found, the level of activation of the hippocampus during encoding of the sequence-object associations could also be used to predict later retrieval.  It is possible that binding is not as strong for the flat envelopes, which would be evident only with imaging techniques.

Brain structures differentially contribute to recognition and recall memory (Tsivilis, Vann, Denby, Roberts, Mayes, Montaldi & Aggleton, 2008), which also may help explain why recognition and recall scores were so different across conditions. It might be an informative endeavor to see if the strategy employed by the participant to make the sequence-object associations correlated with their subsequent recognition and recall scores. Participants often reported using highly visual strategies, including visualizing the rises and drops of the frequency

pattern on a note staph or associating each individual tone in the sequence with a feature on the

object such as a corner or colored button. Zatorre et al. (1994) showed cerebral blood flow

increases in the right occipital cortex when listening to passive melodies (i.e., those not requiring

a pitch judgment), showing that visualization may be common to the auditory experience.

Furthermore, future studies could behaviorally test this strategy idea by instructing participants

to either adopt or not adopt a visualization strategy during encoding.

Given our growing reliance on technology, it would be useful to apply these findings to

the best use of sound in human-computer interfaces. Increasing auditory fidelity is less expensive

than improving graphics (Davis et al., 1999), and also increases the perceived value of the

product (Schutz et al., 2009), both of which could increase profits for technology interface

companies. A reduced learning curve for interfaces, as well as increased usability would be

helpful to the designers and users. The results of this thesis suggest that percussive envelopes

should be used in interfaces to ensure the most cognitive benefit to the user.  Psychology

research, like computer science research, often uses flat amplitude envelopes as well. Again, this

thesis suggests that previous results in the auditory literature on amplitude envelope should be

revisited to ascertain whether they replicate with percussive, naturally-occurring envelopes.  The

use of more ecologically valid amplitude envelopes as auditory stimuli could potentially alter

years of research on auditory perception.

As we increase our understanding of how incoming information is relayed to memory,

the discoveries we make have obvious clinical implications. Although there are many memory-

improving drugs currently on the market, it is not entirely clear why or how they work. If we can

discern why and how some information has a cognitive advantage in learning and memory, we

may be able to better inform pharmacological pursuits. Improving memory even in non-clinical

populations is of extreme interest, especially when considering that memories tend to shape our perception of self.

The purpose of this thesis was to further explore previous research (Schutz et al., 2009) that discovered an intriguing effect of amplitude envelopes on the ability to make object-sequence associations. We therefore set out to identify basic characteristics of this effect. We found that this effect does not act on a discrete process within learning and memory (e.g. encoding and retrieval), but rather is intrinsic to the information supplied by the percussive amplitude envelope. By testing a second artificial, but percussive amplitude envelope, we found that the percussive amplitude envelope only provides a cognitive advantage when it is ecologically valid, suggesting that the ecological validity of the amplitude envelope is either the cause of or a large contributor to this effect.

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