The Classic Stroop Asymmetry Works for Spoken as Well as Written Words
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ABSTRACT. In modern versions of the Stroop task, participants view target words presented on a computer screen with pixels that are either congruent (e.g., “Red” in red pixels) or incongruent (e.g., “Red” in blue pixels) with the meaning of the target word. When participants report the target color, the difference in response time between congruent and incongruent targets (i.e., Stroop effect) is typically larger than when they report the target word (i.e., reverse Stroop effect); this is the classic Stroop asymmetry. For decades following Stroop’s experiments, the prevailing explanation for the asymmetry asserted that, for most people, word reading but not color naming has become automatic, so the target word should always become mentally accessible before the target color. Recent studies have argued instead that the advantage for the target word results not from automaticity but from a strong association between the identification task and verbal processing. To test the strength-of-association account, we developed Qualtrics scripts to deliver visual and auditory target words in Stroop and reverse Stroop tasks. The visually presented targets replicated the classic Stroop asymmetry, $p < .001, \eta_p^2 = .27$. The auditorily presented targets extended the classic Stroop asymmetry to the auditory domain, $p < .001, \eta_p^2 = .18$. These results support the argument that, for an identification task, the target’s semantic features enjoy an advantage over the target’s perceptual features regardless of the sensory modality to which the target is presented. In turn, this shows that task demands are more important than automaticity in mental processing.

Keywords: Stroop effect, reverse Stroop effect, Stroop asymmetry, auditory Stroop effect, online data collection

Most people can walk and chew gum at the same time. Both walking and chewing have been practiced to the point where they no longer require attention, so neither activity hinders the other. In contrast, for a task requiring attentional focus, an irrelevant distraction can leak through the attentional filter to interfere with it (Appelbaum et al., 2014; Linzarini et al., 2017). One of the most widely used experimental paradigms for studying mental interference is the Stroop task (MacLeod, 2005). In a typical modern version of the Stroop (1935) task, participants view a target word on a computer screen written with pixels that are either congruent with the target’s meaning (e.g., “Red” written with red pixels) or incongruent (“Red” written with blue pixels). When the participants’ task is to identify the target’s pixel color, response times (RT) for incongruent targets are generally longer than for congruent targets, and this RT difference between incongruent and congruent targets is called the Stroop effect (Whitehead et al., 2018). On the other hand, when the participants’ task is to identify the target word rather than the target color, the RT difference between incongruent and congruent targets (i.e., the reverse Stroop effect) is much smaller. This disparity between large Stroop effects and small reverse Stroop effects is called the classic Stroop asymmetry (Melara & Algom, 2003). The reasons for the classic Stroop asymmetry have been widely debated, and here we aim to extend on a recent idea for why it happens.

Horse Race Model: Classic Stroop Asymmetry is Due to Automaticity of Reading
The most prominent early theory of the classic Stroop asymmetry asserted that people who have spent a lifetime reading can identify written words without any need for
attentional control, whereas identifying colors has not been practiced as extensively, so it still requires attentional control (Dunbar & MacLeod, 1984). In other words, word reading but not color naming has become automatic. Thus, when participants identify the target color in a Stroop condition, the automaticity of reading makes the identity of the target word mentally accessible more quickly than controlled processing can make the identity of the target color accessible, so an incongruent target word has the opportunity to interfere with identification of the target color. But when participants identify the target word in a reverse Stroop condition, the target color lags behind the target word so an incongruent target color has no opportunity to interfere with identification of the target word. This simple horse race model implies that the target word always beats the target color to the finish line, so the Stroop effect should always be larger than the reverse Stroop effect.

And yet, Uleman and Reeves (1971) described an experiment in which the Stroop effect was smaller than the reverse Stroop effect, thereby undermining the horse race model of the classic Stroop asymmetry. They presented participants with paper cards on which the researchers had written numerous color words with either congruently or incongruently colored ink. Participants scanned the cards for a target word in one condition (i.e., Stroop) or target ink color in the other condition (reverse Stroop) and wrote checkmarks next to the targets. Uleman and Reeves found that interference from incongruent words in the Stroop condition was less than from incongruent colors in the reverse Stroop condition. This result demonstrated that the classic Stroop asymmetry could be inverted, but why was it inverted?

**Translation Model: Translation Between Verbal and Visual Codes Can Invert the Classic Stroop Asymmetry**

A possible explanation for the classic Stroop asymmetry in traditional Stroop tasks and the inverted asymmetry in Uleman and Reeves (1971) relies on the claim that verbal and visual information are encoded in, and proceed along, two separate mental processing streams (Song & Hakoda, 2015; Virzi & Egeth, 1985). Because traditional Stroop experiments elicited vocal responses, the visually encoded target color in Stroop conditions required translation into a verbal code to generate a vocal response, which allowed the verbally encoded target word to interfere with response generation. In reverse Stroop conditions, the verbally encoded target word did not require translation to generate a vocal response, so the visually encoded target color did not have the opportunity to interfere. That is, in traditional Stroop experiments, the Stroop condition required translation but the reverse Stroop condition did not.

Thus, the translation account can explain why the Stroop effect has traditionally been larger than the reverse Stroop effect, but what about the inverted asymmetry in Uleman and Reeves (1971)? Because the scanning task in Uleman and Reeves required visual processing rather than verbal processing as in traditional Stroop tasks, the advantage switched from the target word to the target color. That is, when participants generated a manual response to report the target's location, the visually encoded target color did not require translation for the visually encoded target color in Stroop conditions, but did require translation for the target word in reverse Stroop conditions. The translation account predicts that when a Stroop condition does not require translation but a reverse Stroop condition does, the Stroop effect should be smaller than the reverse Stroop effect: an inversion of the classic asymmetry. To verify this prediction of the translation account, Durgin (2000) developed a task in which a Stroop color word (e.g., “Red” written with blue pixels) was surrounded by four patches of color (red, green, blue, and yellow). In the Stroop condition, participants moved the cursor from the target location to the patch that matched the target's pixel color (i.e., the blue patch), and in the reverse Stroop condition, participants moved the cursor to the patch that matched the target word (i.e., the red patch). As predicted by the translation account, in this matching task and others that replicated it (Miller et al., 2016; Song & Hakoda, 2015), the Stroop effect was smaller than the reverse Stroop effect.

**Alternative Explanations of Inverted Stroop Asymmetry: Strength of Association and Response Modality**

Whereas the translation account does explain the inversion of the classic Stroop asymmetry in matching tasks, there are two plausible alternative explanations. First, Blais and Besner (2006) argued that translation may not be necessary to invert the Stroop asymmetry in matching tasks, insofar as the visual nature of the matching task itself may be sufficient to afford an advantage to the target's visual feature (i.e., pixel color). Because a matching task is more strongly associated with visual processing than verbal processing, this is called the strength-of-association account. And second, Grégoire et al. (2019) noted that many studies that have demonstrated significant reverse Stroop effects (Blais & Besner, 2006, 2007; Durgin, 2000; 2003; Miller et al., 2016; Song & Hakoda, 2015; Uleman & Reeves, 1971; Yamamoto et al., 2016) elicited manual responses rather than vocal responses as in traditional Stroop experiments.

Sobel et al. (2020) aimed to test the prediction made by the strength-of-association account (Blais & Besner, 2006) that a task which is strongly associated with visual processing
is sufficient to invert the classic Stroop asymmetry. To do so, they manipulated the task between experiments; in one experiment, participants identified (i.e., using verbal processing) the target word or color, and in another experiment, they localized (i.e., reported the location of, using visual processing) the target based on its word or color. At the same time, they controlled for the contributions of response modality (Grégoire et al., 2019) and translation (Durgin, 2000). To control response modality, manual responses were required in both experiments. Translation was controlled by eliminating the need for translation between the cue feature and target feature, so a color patch cue indicated the target color in the Stroop condition, and a word cue indicated the target word in the reverse Stroop condition. The identification experiment replicated the classic Stroop asymmetry; the Stroop effect was larger than the reverse Stroop effect. Because this task elicited manual responses, the resulting classic Stroop asymmetry is inconsistent with the response modality account, which asserts that manual responses should invert the asymmetry. Apparently, the task demands of identification encouraged participants to covertly map verbal codes onto the manual responses, so the manual responses were verbally mediated (Bearden et al., 2021; Blais & Besner, 2006; Parris et al., 2019; Sugg & McDonald, 1994). Then, in the localization experiment, the classic asymmetry was inverted; the Stroop effect was smaller than the reverse Stroop effect.

Testing the Strength-of-Association Model: Auditory Presentation

Thus the results from Sobel et al. (2020) and others (Diaz-Piedra et al., 2022; Smith et al., 2022) supported the strength-of-association account by showing that verbally mediated tasks elicit a classic Stroop asymmetry, and visually mediated tasks invert the classic Stroop asymmetry. Furthermore, by controlling for translation and response modality while manipulating task demands, the inversion of the Stroop asymmetry between verbally and visually mediated tasks could not be explained by the translation or response modality accounts. Here we aimed to provide further support for the strength-of-association account by testing another of its predictions. That is, given the strong association between an identification task and verbal processing, the identification task should confer an advantage on a verbal target feature over a perceptual target feature; furthermore, this advantage over a perceptual feature should not be limited to just a visual feature as in traditional Stroop tasks, but should extend to other sensory modalities. To test this hypothesis, we presented visual targets as in traditional Stroop tasks in Experiment 1, and presented auditory targets in Experiment 2.

While auditory Stroop tasks have addressed various kinds of conflict between the perceptual and semantic aspects of a spoken word such as gender (e.g., Knight & Heinrich, 2017), we thought that a more appropriate analogy for the pixel color of written words would be a basic perceptual feature such as pitch. As with the visual color-word Stroop task, demonstrations of the auditory Stroop effect for pitch are common (Donohue et al., 2012; Morgan & Brandt, 1989) but demonstrations of the auditory reverse Stroop effect are scarce. As Blais and Besner (2006) argued about the visual Stroop effect, there is no way to tell if nobody has looked for a reverse auditory Stroop effect for pitch, or if instead everyone who has tried to find an effect has found a null effect (the file drawer problem; Rosenthal, 1979). As with the visual Stroop asymmetry, one workaround for null effects in auditory reverse Stroop tasks would be to carry out both Stroop and reverse Stroop tasks, then a large Stroop effect along with a small or null reverse Stroop effect could yield a significant two-way interaction effect.

Indeed, Akiva-Kabiri & Henik (2012) designed a hybrid visual-auditory task that included both Stroop and reverse Stroop tasks. Participants were trained musicians who heard a musical note while viewing the written name of a note. Because participants in traditional Stroop conditions report the target’s perceptual feature (color) and in reverse Stroop conditions report the target’s semantic feature (word), the analogous tasks were auditory tone naming and visual notation naming. The authors found a classic Stroop asymmetry: incongruent written notation interfered with naming the note more than the auditory note interfered with naming the visual notation. Here we sought to demonstrate a classic Stroop asymmetry for auditory presentation of words for participants who were from a general undergraduate student population rather than trained musicians.

Rationale and Hypotheses

In this paper we aimed to test the prediction made by the strength-of-association account that the strong association between identification tasks and verbal processing should confer an advantage on a target’s verbal feature over its perceptual feature, regardless of the sensory modality to which the targets are presented. To do so, in Experiment 1 we presented visual images of the target words, and in Experiment 2 we presented auditory recordings of the target words. Ideally, these experiments would have been carried out in a laboratory setting that could reduce ambient noise and other distractions to a minimum. Unfortunately, in the wake of the global pandemic, many students at our university remain anxious about face-to-face participation in experiments. In the light of this reality, we decided to take the opportunity to deliver our experimental materials remotely.
Of course, remote delivery of experimental materials entails the introduction of much unavoidable variability to the testing environment because participants use their own devices and operating systems, and carry out the experiments in settings of their choosing while possibly engaged in other activities such as eating dinner or watching television. These sources of variability can threaten the precision of timing for experiments such as Stroop tasks that measure RT as a dependent variable (Anwył-Irvine et al., 2021). Nevertheless, a recent study (Smith et al., 2022) demonstrated that delivering experimental materials via Qualtrics, a popular online platform for online data collection (Belliveau et al., 2022; Greene & Naveh-Benjamin, 2022), could replicate the results from a previous study carried out in a laboratory setting (Sobel et al., 2020) in which the manipulation of task demands inverted the classic Stroop asymmetry between conditions. To compensate for the additional variability inherent with remote delivery of Stroop materials, Smith et al. had larger sample sizes (i.e., 83 and 90 for convenience samples, 160 and 144 for nationwide samples) than the 10 to 20 participants per condition that are common in Stroop experiments conducted in the laboratory (Blais & Besner, 2007; Dunbar & MacLeod, 1984; Durgin, 2000; Machado-Pinheiro et al., 2010; Miller et al., 2016; Sobel et al., 2020; Song & Hakoda, 2011, 2015). Here we sought to replicate and extend on the remote delivery of Stroop experiments via Qualtrics demonstrated by Smith et al.

In the first of two experiments, we intended to replicate a classic Stroop asymmetry in which participants accessed the experiment remotely (as in Smith et al., 2022). A Qualtrics script presented Stroop color word stimuli, and asked participants to report the target color in the Stroop condition and the target word in the reverse Stroop condition. We hypothesized that RT differences between congruent and incongruent targets should be larger for the Stroop condition than the reverse Stroop condition. In Experiment 2, Qualtrics delivered prerecorded sound files in which confederates said either “high” or “low” while speaking in either a high or low tone of voice. The equivalent of a Stroop condition was when participants reported the perceptual feature (high or low tone), and reverse Stroop condition was when they reported the verbal feature (the word “high” or “low”). We hypothesized that the classic Stroop asymmetry would extend to auditory presentation, so the RT difference between congruent and incongruent targets should be greater when participants reported the target’s voice tone than when they reported the target word.

**Experiment 1: Visual Presentation**

**Method**

**Participants**

In both experiments, participants were undergraduate students at a mid-sized university in the Southern United States who participated in exchange for credit in their designated psychology courses. Our proposal entitled *Spatial Interference* was approved by the UCA Institutional Review Board, and we treated all participants in accordance with the ethical standards established by the American Psychological Association (2017). To determine an appropriate sample size that could reliably distinguish between a Stroop effect and reverse Stroop effect, a pilot experiment yielded a Cohen’s $d$ of 0.32. A power analysis determined that a Cohen’s $d$ of 0.30 would require a sample size of 54 participants to achieve 80% power at an alpha of .01 (Bausell & Li, 2002). Our sample for Experiment 1 included 80 participants, 67 of whom identified as female, 12 as male, and one as nonbinary. The proportion of female participants in our sample (83.75%) is consistent with the proportion of female students who take psychology courses in our department, which has hovered around 82% over the last few years. Participants’ ages ranged from 18 to 59 years with a mean of 21.49 and standard deviation of 5.77. There were 64 participants who described themselves as White, seven as Hispanic, five as Black or African American, two as Asian American, one as Native Hawaiian or Pacific Islander, and one preferred not to report a race.

The Qualtrics script randomly assigned half of the participants to report the target pixel color (Stroop) in the first block and the target word (reverse Stroop) in the second block; block order was counterbalanced across participants so the other half of participants reported the target word (reverse Stroop) in the first block and target pixel color (Stroop) in the second. The two independent variables were the reported target feature (i.e., target color in the Stroop condition, target word in the reverse Stroop condition) and congruity between the target color and word. Both variables were manipulated within participants, with each level of reported target feature presented in its own block as just described, and both levels of congruity randomly interleaved within each block. The dependent variable was the time between the onset of each visual display and the response (i.e., RT).

**Apparatus**

Participants logged in to their accounts on SONA (uca.sona-systems.com) to sign up for the experiment. The SONA website then redirected them to the script on
Qualtrics, which they could complete by using their own personal devices.

**Stimuli**

At the beginning of each trial, a prompt (i.e., “Click here to start the next trial”) directed participants to click a button in the middle of the display so the cursor would be centered before participants selected one of four responses. Clicking the button caused a new page to appear that contained a target word that was one of the four color words “Red,” “Green,” “Blue,” or “Yellow,” written with pixels in one of the four colors, above four radio buttons. In the Stroop condition, the radio buttons were each labeled with one of four rectangular color patches containing red, green, blue, or yellow pixels, respectively. In the reverse Stroop condition, the radio buttons were each labeled with one of four color words written in black pixels, arranged in the same order as in the Stroop condition. When participants selected the correct response, the stimulus page was replaced by the cursor-centering page for the next trial. When they selected an incorrect response, a page with the following message appeared: “The answer you provided was incorrect. Please try to select the right answer.” To start the next trial after receiving this admonition, participants needed to click the advance button. We hoped this extra step for mistaken responses would provide an incentive to select correct responses.

**Procedure**

The Qualtrics script began by presenting an informed consent letter, then a page containing demographics questions. Next, a brief set of instructions informed the participants that they would see a series of words written with pixels that were either congruent or incongruent with the words’ meanings. Participants who were assigned to the Stroop condition in the first block were instructed to report each target color, and the remaining participants were instructed to report each target word. The Appendix contains the instructions that preceded each of the two blocks for both experiments. The experiment began when participants clicked the Qualtrics Advance button.

The first four trials in each block were practice trials and excluded from analysis, followed by 32 experimental trials. Each of the four congruent targets (e.g., “Red” written with red pixels) were presented four times in each block. The incongruent targets included two repetitions of each of the following eight word–color combinations (summarized in Table 1): the word “Red” written in green pixels, “Red” in blue pixels, “Green” in red pixels, “Green” in yellow pixels, “Blue” in red pixels, “Blue” in yellow pixels, “Yellow” in green pixels, and “Yellow” in blue pixels. Thus, there were a total of 16 congruent targets and 16 incongruent targets in each block, presented in random order. At the end of the first block, a page informed participants they had completed one half of the experiment, and that for the remainder of the experiment they should report the other target feature. The second block began when participants clicked the Advance button.

Each page that contained a target and response buttons also included a timer that recorded the time between the onset of the page and the respondent’s first and last mouse clicks on the page, as well as the total number of mouse clicks. As described below, the parameters measured by the timer formed the basis for measuring the dependent variable, RT. As is standard in Stroop experiments in general and in Qualtrics scripts in particular, the timing mechanism was invisible to participants. Because Stroop tasks are intended to measure attentional interference, informing participants about the real time progress of a timing mechanism would introduce a conspicuous but irrelevant distraction to the stimulus presentation. In the debriefing at the end of the experiment, participants were informed that we were trying to find out if they were slower to respond to incongruent targets than to congruent targets.

**Results**

Before submitting RTs to a two-way ANOVA in SPSS with congruity and reported feature (pixel color or word) as within-subjects factors, we removed the results from specific trials for any of three reasons. First, we removed trials in which participants provided an incorrect response; for example, if a target in the Stroop condition was “Red” in blue pixels, the correct response would be the patch made from blue pixels, and any other response would be incorrect. Next, we removed any trials in which there was more than one mouse click. Our rationale for doing so is as follows. When participants selected one

<table>
<thead>
<tr>
<th>TABLE 1</th>
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<tr>
<td><strong>Combinations of Word and Pixel Color Used for Incongruent Targets in Experiment 1</strong></td>
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<tr>
<td>Target Word</td>
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<tr>
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of the four responses with their first mouse click, the time to first mouse click represented their RT for that trial. Because the script automatically advanced (to the next trial for correct responses or the error message for incorrect responses) when participants clicked any of the response buttons, in trials with more than one mouse click, the participant's first mouse click must have been somewhere on the page that was not on one of the response buttons. For that reason, we believed that in trials with more than one mouse click, the time to first mouse click should not be interpreted as representing the RT, and the time of the last mouse click was also not readily interpretable. This rationale is consistent with a previous study in which Stroop experimental materials were delivered remotely via Qualtrics (Smith et al., 2022).

Finally, after removing any trials with incorrect responses or more than one mouse click, we calculated the mean and standard deviation of each participant's RTs. An initial examination of the data revealed that most RTs were on the order of three seconds or less, but some RTs were much longer, and even minutes long. Because participants carried out the experiment in settings of their choosing, we believe these much longer RTs did not reflect the time required to select and initiate a response, but instead indicate that participants got distracted by a concurrent task. The trick is to distinguish between valid cases in which participants actually generated a response as instructed but took an unusually long time to do so, from invalid cases in which participants were carrying out a completely different task. A simple, relatively effective, and widely accepted method to eliminate the influence of invalid trials is to exclude any values that are more than three standard deviations greater than the overall mean (Osborne & Overbay, 2004). With that in mind, for each participant we removed all RTs that were more than three standard deviations greater than that participant's mean RT. The percentage of trials removed for incorrect responses, extra mouse clicks, or being an outlier are presented in Table 2. The remaining RTs were then used to calculate the means for each participant and condition.

After removing trials with errors, extra clicks, and outliers, the means of the remaining RTs (depicted in Figure 1) were submitted to a two-way ANOVA in SPSS with congruity and reported feature (pixel color or word) as within-subjects factors. Responses were faster for congruent targets than incongruent, \( F(1, 79) = 61.60, p < .001, \eta_p^2 = .44 \), but RTs were not significantly different when the participants reported the target color (Stroop) and when they reported the target word (reverse Stroop), \( F(1, 79) = 3.22, p = .08, \eta_p^2 = .04 \). The interaction between congruity and reported feature, \( F(1, 79) = 28.81, p < .001, \eta_p^2 = .27 \), shows that the Stroop effect was different from the reverse Stroop effect. Simple effects analysis showed that both the Stroop effect, \( F(1, 79) = 78.00, p < .001, \eta_p^2 = .50 \), and reverse Stroop effect, \( F(1, 79) = 14.30, p < .001, \eta_p^2 = .15 \), were significant, and confirmed that the Stroop effect size \( (\eta_p^2 = .50) \) was larger than the reverse Stroop effect size \( (\eta_p^2 = .15) \).

Although RT differences between Stroop and reverse Stroop conditions are more robust than error rate differences, when error rate differences are significant, they tend to increase along with RTs; conditions with slower responses tend to have higher error rates than conditions with faster responses (Kane & Engle, 2003; Meier & Kane, 2013). To see if that pattern applied to our results, we submitted the percentages of errors, extra clicks, and outliers (summarized in Table 2) each to its own two-way ANOVA in SPSS with congruity and reported feature (pixel color or word) as within-subjects factors. Error rates were higher for the incongruent targets than for congruent targets, \( F(1, 79) = 7.80, p = .007, \eta_p^2 = .04 \), and outlier rates were higher for the incongruent targets than for congruent targets.

### TABLE 2

<table>
<thead>
<tr>
<th></th>
<th>Congruent Errors</th>
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<th>Congruent Outliers</th>
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<th>Incongruent Clicks</th>
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<tr>
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### FIGURE 1

Mean Response Times for Experiments 1 and 2

Note: Error bars represent 95% confidence intervals (calculation based on Loftus & Masson, 1994).
For visual presentation in Experiment 1, participants reported the target’s perceptual feature (color) in the Stroop condition and the target’s semantic feature (word) in the reverse Stroop condition, so the equivalent features for auditory presentation in Experiment 2 would be the target’s tone in the Stroop condition and the target word in the reverse Stroop condition. Although the reported features were different in the two experiments, the underlying experimental design remained the same as in Experiment 1; the two levels of reported feature were organized by block and two levels of congruity were randomly interleaved within blocks. Participants were exposed to a Stroop condition in one block and a reverse Stroop condition in the other block, and block order was randomly assigned and counterbalanced across participants.

Apparatus
As in Experiment 1, participants used their own personal devices to access their Sona account, which redirected them to the Qualtrics script.

Stimuli
We recruited two female and two male confederates and recorded them saying the words “High” and “Low,” each word in a high tone of voice and low tone of voice, then uploaded the sound files to Qualtrics. Each trial began with a cursor-centering page, and when participants clicked the button a stimulus page appeared and played one of the 16 sound files. In the Stroop condition, the stimulus page contained two radio buttons labeled “High tone” and “Low tone” respectively, and in the reverse Stroop condition, the buttons were labeled “High” and “Low.”

Procedure
As in Experiment 1, the Qualtrics script began by presenting three pages containing an informed consent letter, demographics questions, and instructions (presented in the Appendix), in that order. The 16 sound files (eight of them congruent and eight incongruent) were presented twice in each block, in random order. After proceeding through four practice trials excluded from analysis and 32 experimental trials, participants were informed that they had completed the first half of the experiment, and that for the remainder of the experiment they should report the other target feature. A timer on each stimulus page recorded the time to the first and last mouse clicks on the page, and the total number of mouse clicks.

Results
As in Experiment 1, we removed all trials that had incorrect responses, more than one mouse click, or any participant’s RTs that were more than three standard deviations greater than the mean for that congruency condition. For RT, we removed all trials that were more than three standard deviations greater than the mean for that congruency condition. For error rate, we used a conservative criterion of 2%.

Discussion
The RT results from the identification task replicated the classic Stroop asymmetry; the Stroop effect was larger than the reverse Stroop effect. Because we obtained a classic Stroop asymmetry for a task that elicited manual responses, our results do not support the argument that vocal responses induce the classic Stroop asymmetry and manual responses invert the asymmetry (Grégoire et al., 2019). But our results do support the argument that in identification tasks with manual responses, participants covertly map verbal labels onto the responses (Bearden et al., 2021; Blais & Besner, 2006; Parris et al., 2019; Sugg & McDonald, 1994). Furthermore, the remote delivery of the experimental materials introduced variability that would not occur in a laboratory setting (Anwyl-Irvine et al., 2021). The emergence of a classic Stroop asymmetry for RT in the midst of so much uncontrollable variability highlights the robustness of the classic asymmetry, and suggests that it may generalize to auditory presentation of the stimuli for the same experimental conditions and manual responses.

Experiment 2: Auditory Presentation

Method
Participants
Our sample for Experiment 2 included 80 participants, 60 of whom identified as female, and 20 as male. As in Experiment 1, the proportion of female participants in our sample for Experiment 2 (75.00%) is consistent with the 82% of female students who have taken psychology courses in our department over the last few years. Participants’ ages ranged from 18 to 55 years with a mean of 20.54 and standard deviation of 4.61. There were 53 participants who described themselves as White, 14 as Black or African American, seven as Hispanic, four as Asian American, one as Native Hawaiian or Pacific Islander, and one preferred not to report a race.
deviations greater than that participant’s mean RT. In Experiment 1, after removing errors, extra clicks, and outliers, every participant retained at least half of the trials in every condition. In contrast to Experiment 1, in Experiment 2 there were nine participants for whom the total number of removed trials was more than half (eight out of 16) of the trials in at least one of the four conditions (i.e., Stroop and reverse Stroop, congruent and incongruent). After removing the data from these nine participants, the RTs from the remaining 71 participants were analyzed (see Table 2 for the percentage of errors, extra clicks, and outliers for the remaining 71 participants).

Mean RTs (depicted in Figure 1) were submitted to a two-way ANOVA in SPSS with congruity and reported feature (voice tone or word) as within-subjects factors. Responses were faster for congruent targets than incongruent, $F(1, 70) = 30.37, p < .001, \eta^2_p = .30$, and were slower when participants reported the target tone (Stroop) than when they reported the target word (reverse Stroop), $F(1, 70) = 71.69, p < .001, \eta^2_p = .51$. The significant interaction between congruity and reported feature, $F(1, 70) = 15.04, p < .001, \eta^2_p = .18$, shows that the Stroop effect was different from the reverse Stroop effect. Simple effects analysis confirmed that the Stroop effect was significant, $F(1, 70) = 31.57, p < .001, \eta^2_p = .31$, but the reverse Stroop effect was not, $F(1, 70) = 0.09, p = .76, \eta^2_p = .001$, and the Stroop effect size ($\eta^2_p = .31$) was larger than the reverse Stroop effect size ($\eta^2_p = .001$).

The percentages of errors, extra clicks, and outliers (summarized in Table 2) were each submitted to their own two-way ANOVA in SPSS with congruity and reported feature (voice tone or word) as within-subjects factors. Error rates were higher for the incongruent targets than for the congruent targets, $F(1, 70) = 93.06, p < .001, \eta^2_p = .57$, and when participants reported the target tone (Stroop) than when they reported the target word (reverse Stroop), $F(1, 70) = 44.95, p < .001, \eta^2_p = .39$, and the interaction between congruity and reported feature, $F(1, 70) = 42.29, p < .001, \eta^2_p = .38$, shows that the Stroop effect for error rates was different from the reverse Stroop effect. Simple effects analysis confirmed that the Stroop effect was significant, $F(1, 70) = 97.21, p < .001, \eta^2_p = .58$, but the reverse Stroop effect was not, $F(1, 70) = 3.49, p = .07, \eta^2_p = .05$, and the Stroop effect size ($\eta^2_p = .58$) was larger than the reverse Stroop effect size ($\eta^2_p = .05$). None of the effects for extra clicks or outliers reached significance (all $p > .05$). In contrast to Experiment 1, which failed to provide evidence of a classic Stroop asymmetry for error rates, in Experiment 2 there was a classic Stroop asymmetry for error rates.

**Discussion**

Auditory presentation elicited a classic Stroop asymmetry for both RT and error rates. As with the classic Stroop asymmetry for RT in Experiment 1, the Experiment 2 results do not support the response modality account of the classic Stroop asymmetry (Grégoire et al., 2019) but do support the hypothesis that for identification tasks, manual responses are verbally mediated (Bearden et al., 2021; Blais & Besner, 2006; Parris et al., 2019; Sugg & McDonald, 1994). Furthermore, auditory presentation introduced even more variability into the experimental materials than was the case for visual stimuli; specifically, participants controlled the loudness of the sound files playing on their devices. The fact that we obtained a significant interaction between congruity and reported feature for both RTs and error rates amidst all the variability entailed by remote presentation suggests that experimenters should not avoid the reverse auditory Stroop task in fear that they will obtain a null effect. We hope this result emboldens other researchers to carry out auditory reverse Stroop tasks, because a null effect for an auditory reverse Stroop task along with a large auditory Stroop effect could produce a significant interaction, so these results will not languish in a file drawer (Rosenthal, 1979).

**General Discussion**

Stroop effects that are larger than reverse Stroop effects are so widespread in the literature that the asymmetry has been dubbed a classic (Melara & Algom, 2003). Whereas the classic asymmetry is commonplace in traditional Stroop experiments that elicit vocal responses to identify the target features (Blais & Besner, 2006), experiments that elicit manual responses to localize the target invert the asymmetry (Durgin, 2000; Miller et al., 2016; Song & Hakoda, 2015; Uleman & Reeves, 1971). This inversion could result from the response modality (vocal versus manual) or the mental processing associated with the task (verbal processing for identification tasks, visual processing for localization tasks). Nevertheless, experiments that manipulated the task while controlling for response modality (Diaz-Piedra et al., 2022; Smith et al., 2022; Sobel et al., 2020) demonstrated that the strength of association between the mental processing stream of the target feature and the task is the key; a verbally mediated identification task elicits a classic Stroop asymmetry, whereas a visually mediated localization task elicits an inverted Stroop asymmetry, even when both tasks entail manual responses. Given the strength of association between verbal processing and an identification task (Blais & Besner, 2006), an identification task should elicit a classic Stroop asymmetry regardless of the sensory modality to
which the target words are presented. Thus, the primary contribution of our study to the Stroop literature is the discovery of a classic Stroop asymmetry for auditory presentation of target words, which provides novel support for the strength-of-association account of the Stroop asymmetry.

**Limitations and Future Directions**

The predictions of the automaticity and strength-of-association accounts are summarized in Table 3. The automaticity account asserts that identification of a written word has become automatic but identification of a perceptual feature has not (Dunbar & MacLeod, 1984). Furthermore, it seems likely that participants have spent more time, effort, and attention throughout their lives identifying spoken words than they have spent identifying the pitch of the speaker's voice, the automaticity account predicts that the Stroop effect should always be larger than the reverse Stroop effect. In contrast, the strength-of-association account (Blais & Besner, 2006) asserts that verbally mediated identification tasks confer an advantage on the target word over the target's perceptual feature (i.e., Stroop effect > reverse Stroop effect), whereas perceptually mediated localization tasks confer an advantage on the target's perceptual feature over the target word (i.e., Stroop effect < reverse Stroop effect). Thus, for traditional Stroop identification of visual targets as in the upper left cell, both automaticity and strength-of-association predict the classic Stroop asymmetry. But for localization of visual targets in the lower left cell (Diaz-Piedra et al., 2022; Smith et al., 2022; Sobel et al., 2020), the inversion of the classic Stroop asymmetry in these studies is consistent with the strength-of-association account but not automaticity.

A primary limitation of our study becomes apparent when considering our experiments, which involve the identification of auditory targets, and therefore inhabit the upper right cell of Table 3. Whereas we have argued that our results are consistent with the strength-of-association account, our results, which demonstrate a classic Stroop asymmetry, could also be explained by the automaticity account. Although we would argue that the automaticity account had already been discredited by the experiments involving the localization of visual targets (Diaz-Piedra et al., 2022; Smith et al., 2022; Sobel et al., 2020), a skeptic could respond that auditory processing is sufficiently distinct from visual processing that conclusions based on visual presentation do not extend to auditory presentation.

A second limitation of our study is the preponderance of female participants in our sample. Although we are unaware of any studies that have looked at the role of gender differences in the Stroop asymmetry, by extrapolating on what is known about gender differences in mental processing we might speculate about how such a skewed sample might affect our results. Whereas the role of gender differences in mental processing is slight (Ardila et al., 2011), there is some evidence that women have superior verbal processing than men, who have superior visuospatial processing than women (Yeo et al., 2016). With that in mind, a target's verbal feature may become mentally accessible faster than the target's perceptual feature for women because of their superior verbal processing. Accordingly, any sample with a preponderance of female participants should evince a classic Stroop asymmetry. In response, we would argue that a preponderance of female participants does not necessarily entail a classic Stroop asymmetry, because in the first of two Stroop experiments delivered remotely via Qualtrics, Smith et al. (2022) had two samples in which female participants predominated, and yet they found a classic Stroop asymmetry for identification as well as an inverted asymmetry for localization. But then the same skeptic we imagined above would once again claim that results from experiments with visual presentation do not extend to experiments with auditory presentation. Thus it seems that our results are consistent not just with strength-of-association, but also with automaticity and gender differences in mental processing. Nevertheless, even if we accept the skeptic's claim that results from experiments with visual presentation do not extend to experiments with auditory processing for the sake of argument, we can imagine an experiment that could provide definitive support for our claim that a classic Stroop asymmetry for auditory presentation of targets supports the strength-of-association account. The key lies in the lower right cell of Table 3, which is currently empty of any existing experiment involving localization of auditory targets. Such an experiment should be able to select a winner from the

<table>
<thead>
<tr>
<th></th>
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<th>Auditory presentation</th>
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<tr>
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<tr>
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strength-of-association, automaticity, and gender differences in mental processing hypotheses, but only for an experiment in a laboratory setting where the researchers can specifically arrange the locations of a computer and speakers. And this reveals a third limitation of our study: by delivering our experimental materials remotely, we were unable to carry out the critical experiment in the lower right cell in Table 3.

The critical experiment might work as follows. In a laboratory equipped with a computer connected to two speakers located on either side of the computer, we would play the same 16 sound files we used for this study. For each trial, one sound file would be routed to the right speaker and another sound file would be routed to the left speaker. The two sound files would both be either congruent (e.g., “High” in a high tone for the right speaker and “Low” in a low tone for the left speaker) or incongruent (e.g., “High” in a low tone for the right speaker and “Low” in a high tone for the left speaker). In the Stroop condition, participants would report the location (either right or left) of a target defined by its tone, and in the reverse Stroop condition they would report the location of a target defined by its meaning. Because auditory localization depends on perceptual processing, strength-of-association predicts the target tone should have an advantage over the target’s meaning, resulting in a Stroop effect that would be smaller than the reverse Stroop effect. Because the gender ratio in our department’s course should remain stable over the next few years, we expect that female participants should predominate in any future sample just as they did in the samples for this study. Thus, both automaticity and gender differences in mental processing predict an advantage for the target’s meaning over the target tone; the Stroop effect would be larger than the reverse Stroop effect. If this critical experiment finds a smaller Stroop effect than the reverse Stroop effect, the strength-of-association account would be consistent with all four cells in Table 3, and the automaticity and gender differences in mental processing accounts would be consistent with just the upper two cells.

Conclusions

In two experiments, we carried out Stroop and reverse Stroop tasks with visual and auditory stimuli delivered remotely. The uncontrollable variability in the experimental materials entailed by remote delivery relative to a laboratory setting (Anwyl-Irvine et al., 2021) implies that the classic Stroop asymmetries obtained in both experiments are robust effects. In turn, the classic Stroop asymmetry demonstrates that the targets’ verbal features enjoyed an advantage over the perceptual features, even though we elicited manual responses. This lends further support to the argument that in Stroop identification tasks, participants covertly map verbal labels onto the manual responses. We argued that these results support the extension of the strength-of-association (Blais & Besner, 2006) and verbal mediation (Bearden et al., 2021; Blais & Besner, 2006; Parris et al., 2019; Sugg & McDonald, 1994) hypotheses, but not the response modality hypothesis (Grégoire et al., 2019), to the auditory domain. Nevertheless, we also acknowledged that our results could be seen as consistent not just with strength-of-association, but also with automaticity (Dunbar & MacLeod, 1984) and gender differences in mental processing (Yeo et al., 2016) hypotheses. Nevertheless, our project sets the stage for future experiments that could provide more definitive support for strength-of-association as the explanation for the Stroop asymmetry, once participants are ready and willing to return to experiments in the laboratory.

References


Author Note. We have no known conflict of interest to disclose. Correspondence concerning this article should be addressed to Kenith V. Sobel, Department of Psychology and Counseling, University of Central Arkansas, Conway, AR 72035. Email: ksobel@uca.edu
## APPENDIX

### Instructions provided for each experiment, block order, and block

<table>
<thead>
<tr>
<th>Experiment 1: Visual presentation</th>
<th>Experiment 2: Auditory presentation</th>
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<tr>
<td><strong>Block order: Stroop then reverse Stroop</strong></td>
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<td>- In this experiment, you will see a series of target words, one at a time, with pixels that are colored red, green, blue, or yellow. Each target word will be written with blue pixels. Sometimes the color of the target's pixels and the word's meaning will match, and sometimes they won't match. For example, the target word below is 'Red,' but its pixels are colored blue, so this target's color and meaning don’t match.</td>
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<td>- (Here the instructions presented an image containing the word “Red” written with blue pixels)</td>
<td>- There will be two buttons on each screen where audio is played, one that says high tone and one that says low tone. In the first half of the experiment, you should report the target's tone of voice, NOT the target's meaning. Therefore if the word low is said with a high tone of voice, you should report high tone.</td>
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<td>- Below the target will be four buttons, one button next to a patch of red pixels, one next to a green patch, one next to a blue patch, and one next to a yellow patch.</td>
<td>- Click the arrow below to begin the second half of the experiment.</td>
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