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Flexibility of working memory encoding in a sentence–picture–sound verification task

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Dual-process accounts of working memory have suggested distinct encoding processes for verbal and visual information in working memory, but encoding for nonspeech sounds (e.g., tones) is not well understood. This experiment modified the sentence–picture verification task to include nonspeech sounds with a complete factorial examination of all possible stimulus pairings. Participants studied simple stimuli–pictures, sentences, or sounds–and encoded the stimuli verbally, as visual images, or as auditory images. Participants then compared their encoded representations to verification stimuli–again pictures, sentences, or sounds–in a two-choice reaction time task. With some caveats, the encoding strategy appeared to be as important or more important than the external format of the initial stimulus in determining the speed of verification decisions. Findings suggested that: (1) auditory imagery may be distinct from verbal and visuospatial processing in working memory; (2) visual perception but not visual imagery may automatically activate concurrent verbal codes; and (3) the effects of hearing a sound may linger for some time despite recoding in working memory. We discuss the role of auditory imagery in dual-process theories of working memory.

Keywords: Auditory imagery; Working memory; Encoding; Visual imagery; Verbal encoding.

Influential accounts of cognition (e.g., Baddeley & Logie, 1992; Paivio, Clark, Digdon, & Bons, 1989; Wickens, 2002) have emphasised a dichotomy between verbal (symbolic) and visuospatial (analogic) processing during the stage of active information processing that is commonly referred to as working memory. In these dual-process perspectives, words and visual images are handled by independent conceptual mechanisms that work in parallel. Comparatively little attention has been paid to the processing of auditory analogic representations–auditory images of nonverbal acoustic properties of stimuli–in working memory. Current theoretical perspectives leave gaps in their explanations of how nonspeech sounds are remembered and rehearsed, although these activities are clearly pervasive in human cognition (Schellenberg & Trehub, 2003).

This experiment used a verification task to examine auditory imagery, verbal encoding, and visuospatial imagery in working memory; similar tasks have been used extensively to examine the strategies and task dependencies associated with encoding. Clark and Chase (1972) presented simple sentences (e.g., ‘‘star is above plus’’) simultaneously with either a consistent or inconsistent picture. Participants performed a two-choice reaction time task in which they either confirmed or denied that the sentence described the picture. The researchers arrived at a model of the task that presupposed a common, immutable, verbal encoding strategy for both sentences and pictures,

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whereby participants converted both stimuli to propositional representations to perform comparisons.

Tversky (1975) demonstrated the use of a visual imagery strategy in sentence–picture verification with the successive presentation of the picture after a 5 s delay, and Glushko and Cooper (1978) also found evidence of a visual imagery strategy with successive presentation of the sentence followed by the picture. When participants were allowed to control the amount of time they studied the sentence before the picture stimulus appeared, Macleod, Hunt, and Mathews (1978) found a subgroup of participants who were spontaneously forming a mental image of the sentence to compare to the picture during verification.

Mathews, Hunt, and MacLeod (1980) used the sentence–picture verification task to examine flexibility of encoding. Participants were explicitly instructed to use either verbal or visual imagery strategies to accomplish the task. Using verbal encoding, participants' reaction times were extremely consistent with the predictions of a verbal encoding strategy. Mean data during imagery conformed nearly perfectly to the expected patterns of a visual strategy, whereas the mean fit from a spontaneous strategy condition somewhat resembled data from the verbal condition–exactly as would be expected with heterogeneous strategy use with a majority of participants spontaneously favouring a verbal approach. Related work has shown that when participants are not given a specific encoding strategy for the task, they seem to actively adapt their strategy based on task demands, such as the expected format of the verification stimulus (Kroll & Corrigan, 1981; Noordzij, van der Lubbe, & Postma, 2005).

Despite the consistent pattern of results that have emerged from using sentence–picture tasks to study encoding, surprisingly few modifications to the original stimuli and format of the task have been attempted. The fundamental reasoning of stimulus verification paradigms could be adapted to study the encoding of a great variety of stimuli. Further, almost all research using the paradigm has involved unidirectional (sentence–picture) verification tasks; complete factorial manipulations (e.g., including picture–sentence translations) have not been undertaken.

We modified the sentence–picture verification procedure to examine encoding for sentences, pictures, and nonspeech sounds in a three (study stimulus format) by three (encoding strategy) by three (verification stimulus format) within-subjects design. Stimuli depicted simple, fictitious stock states (i.e., either ''price increased'' or ''price decreased''), and the encoding strategy was manipulated at three levels (verbal encoding, visual imagery, and auditory imagery) in different blocks of the study via instructions. Trials consisted of: (1) a study period for a stimulus (a sentence, a picture, or a sound), during which participants encoded the study stimulus as either a verbal representation, a visual image, or an auditory image; (2) a brief delay; and (3) the presentation of a verification stimulus (a sentence, a picture, or a sound) for which participants made a speeded comparison of their encoding to confirm or disconfirm a match with the original stimulus's depicted state for the stock. Regardless of the format of the study stimulus, verification times were predicted to be fastest when the external verification stimulus format matched the format encoded in working memory.

METHOD

Participants

Participants ($N = 48$, 17 females, M age $= 20.0$ years, $SD = 1.7$) were recruited from undergraduate psychology courses and received course credit for their participation in the study.

Apparatus

A program written with Macromedia Director 2004 presented stimuli and collected data. Visual presentations were made on a 43.2 cm Dell LCD monitor. Sounds were presented with Sennheiser HD 202 headphones.

Stimuli

Stimuli were designed to convey information about the stimulus state (increasing or decreasing) as simply as possible. Picture stimuli were unlabelled line graphs–one that showed the stock trend increasing and one that showed decreasing (see Figure 1). Sentence stimuli described the state of the stock with two words–''price increased'' or ''price decreased''–presented in approximately 40 point font at the centre of the screen. Sound stimuli used two discrete tones–C4 (262 Hz) and C5 (523 Hz). Each tone was 100 ms in length (with 10 ms onset and offset ramps) and synthesised with the MIDI piano instrument. The sound represented either an increasing stock price (C4 followed by C5) or a decreasing stock price (C5 followed by C4); higher pitch has been associated with higher position in space (Ben-Artzi & Marks, 1995).

Procedure

Participants were told to remember the state of the stock depicted in the first (study) stimulus for later comparison with the second (verification) stimulus. Participants were given 36 practice trials without a prescribed encoding strategy as an introduction to the task. Participants then experienced 72 trials of each encoding strategy; the order of the encoding strategies was counterbalanced across participants. For a verbatim example of encoding instructions, see the Appendix.

Verbal (sentence) encoding. Participants were instructed to encode the study stimulus as a sentence that stated either ‘‘price increased’’ or ‘‘price decreased’’.

Visual imagery. Participants were instructed to encode the study stimulus as one of the two simple visual images shown in Figure 1.

Auditory imagery. Participants were instructed to encode the study stimulus in pitch memory as one of the two-note sound stimuli, with pitch increasing if the stock price increased or pitch descending if the stock price decreased.

Task. At the beginning of each encoding strategy block, participants confirmed that they understood the prescribed encoding strategy. The trial structure is depicted in Figure 2. Participants kept their left and right index fingers on the ‘‘Z’’ and ‘‘?’’ keys, respectively, and pressed either key to begin a trial. The keypress initiated the study stimulus (a sound, picture, or sentence), and

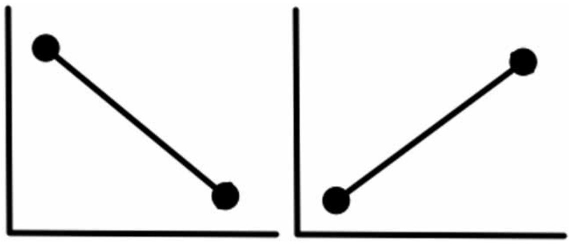

Figure 1. The picture stimuli.

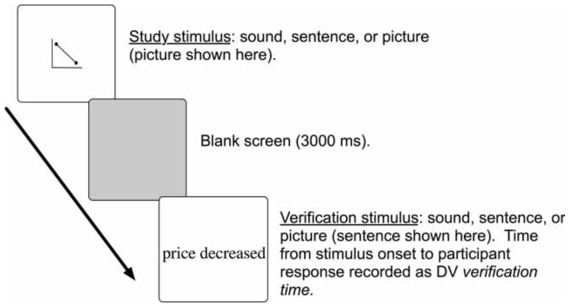

Figure 2. Structure of a trial.

participants encoded the study stimulus according to the assigned strategy. Participants pressed either key when they had encoded the stimulus in the prescribed format, and the verification stimulus appeared after a 3000 ms delay with a blank grey screen. Participants pressed the ‘‘Z’’ key for matches (when the verification stimulus matched the state of their encoding of the study stimulus) or the ‘‘?’’ key for mismatches. The mapping of keys to responses was counterbalanced across participants. Participants were instructed to verify as quickly as possible while following encoding instructions and avoiding errors, and the program provided feedback about verification reaction times following each trial. All possible stimulus combinations appeared twice in the 72 trials per block, and presentations within a block were randomly interleaved. The dependent variable was verification time, defined as the time from the onset of the verification stimulus until the participant pressed a response key to confirm or disconfirm its match with their encoding. The percentage of correct responses was a secondary measure of interest. Each trial (excluding practice) concluded with a brief strategy compliance check; participants self-reported the encoding strategy with which they had accomplished the task (for a description of this manipulation check in our previous work, see Nees & Walker, 2011, p. 312). Participants' choices were limited to ‘‘sound [auditory imagery] strategy’’, ‘‘word [verbal] strategy’’, ‘‘picture [visuospatial imagery] strategy’’, or ‘‘not sure’’. To reduce the potential for demand characteristics to influence responses, the questionnaire instructed: ‘‘Please be honest even if you used the wrong strategy–it is very important that we know which strategy that you used.’’ Participants also were encouraged by the experimenter to accurately report their strategy use, even if they had used the wrong strategy.

RESULTS

One participant failed to follow instructions and was excluded from all analyses. Data for 3.9% of trials were excluded because the participant indicated (s)he did not use the instructed strategy. Individual trials were also excluded from intra-condition means if the verification response was incorrect or if the time was greater than 3 *SD*s from individual condition means; this led to the removal of an additional 7.3% of data across all trials. Data clean-up left empty data cells in the design for 9 additional participants; thus, the final sample size analysed was $N = 38$. Other research using the sentence–picture verification task (e.g., Mathews et al., 1980) reported similar percentages of data elimination.

Analysis of verification times

A repeated measures analysis of variance (ANOVA) was conducted on verification times with Greenhouse-Geisser corrections for sphericity violations. The assumption of sphericity was violated for the main effects of strategy and verification stimulus format, the interaction of strategy with study stimulus format, the interaction of strategy with verification stimulus format, the interaction of study stimulus format with verification stimulus format, and the 3-way interaction, Mauchly's Ws = .16–.78, ps < .05, ∊s = .73–.82. The sphericity assumption held for the main effect of study stimulus, Mauchly's $W = .92$, $p > .05$.

Pairwise comparisons for the significant main effect of strategy, $F(1.65, 60.96) = 3.76$, $p < .05$, $\eta^2_p = .09$, showed that verification times were fastest when participants used the verbal strategy ($M = 942.15$, $SE = 49.17$) as compared to the visual imagery ($M = 1030.88$, $SE = 48.12$), $p < .05$, or the auditory imagery strategy ($M = 1037.83$, $SE = 54.77$), $p < .01$. The visual and auditory imagery strategies were not significantly different, $p > .05$. Pairwise comparisons for the main effect of study stimulus format, $F(2, 74) = 6.13$, $p < .01$, $\eta^2_p = .14$, showed that verification times were fastest when participants had studied sounds ($M = 972.30$, $SE = 40.39$) as compared to sentences ($M = 1015.02$, $SE = 48.39$), $p < .05$, or pictures ($M = 1023.55$, $SE = 49.94$), $p < .01$. The difference between sentences and pictures was not significant, $p > .05$. Pairwise comparisons for the significant main effect of verification stimulus format, $F(1.55, 57.30) = 30.39$, $p < .001$, $\eta^2_p = .45$, showed that verification times were faster when participants verified sentences ($M = 950.27$, $SE = 37.87$), $p < .001$, or pictures ($M = 906.38$, $SE = 47.67$), $p < .001$, as compared to sounds ($M = 1154.22$, $SE = 60.54$). The difference between sentences and pictures was not significant, $p > .05$. Main effects should be interpreted with caution due to the significant interactions.

For the significant interaction of strategy with verification stimulus format, $F(3.14, 116.11) = 27.73$, $p < .001$, $\eta^2_p = .43$, simple effects analyses at each level of the verification stimulus format showed that when the verification stimulus was a sentence (three left bars of Figure 3), participants responded significantly faster using the verbal strategy ($M = 835.74$, $SE = 44.05$) than the visual imagery ($M = 993.26$, $SE = 45.53$), $p < .01$, or auditory imagery ($M = 1021.80$, $SE = 45.79$), $p < .001$, strategies, which were not different from each other, $p > .05$. When the verification stimulus was a picture (three middle bars of Figure 3), participants responded faster using the visual imagery strategy ($M = 814.66$, $SE = 39.43$) than the auditory imagery strategy ($M = 1039.17$, $SE = 65.14$), $p < .001$, but not the verbal strategy ($M = 865.31$, $SE = 55.17$), $p > .05$. The verbal strategy also was significantly faster than the auditory imagery strategy, $p < .001$. When the verification stimulus was a sound (three right bars of Figure 3), participants responded faster using the auditory imagery strategy ($M = 1052.52$, $SE = 66.83$) than the verbal ($M = 1125.41$, $SE = 62.84$), $p < .05$, or visual imagery ($M = 1284.74$, $SE = 73.56$), $p < .001$ strategies. The verbal strategy was significantly faster than visual imagery, $p < .05$.

For the significant interaction of study stimulus format with verification stimulus format, $F(3.03, 112.17) = 8.27$, $p < .001$, $\eta^2_p = .18$, simple effects analyses at each level of the verification stimulus format showed that when the verification stimulus was either sentences or pictures (left and middle three bars of Figure 4, respectively), there were no significant differences as a function of study stimulus format, ps = .088–.821. When the verification stimulus was a sound (right three bars of Figure 4), however, participants were significantly faster to respond if they had studied a sound as compared to sentences, $p < .01$, or a picture, $p < .001$, and there was no difference between sentences and pictures, $p > .05$. The interaction of strategy with study stimulus, $F < 1.00$, and the three-way interaction, $F(5.85, 216.60) = 1.12$, $p > .05$, were nonsignificant.

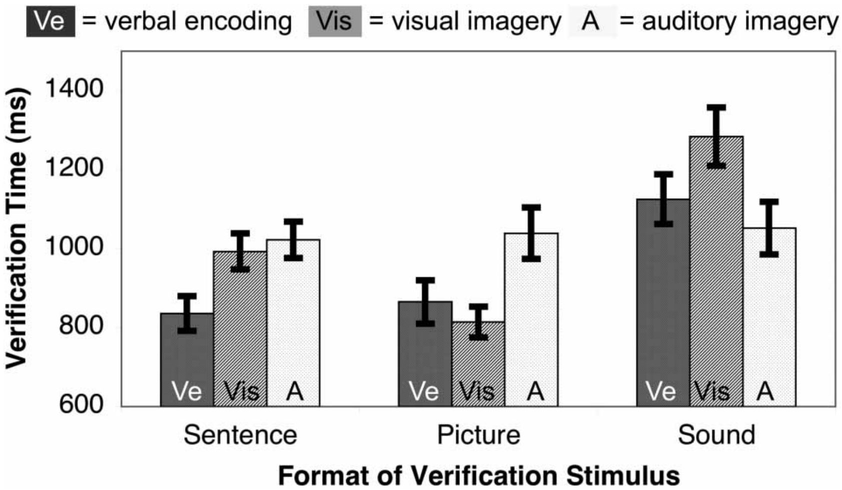

Figure 3. Verification time as a function of encoding strategy and verification stimulus format. Error bars represent *SEM.*

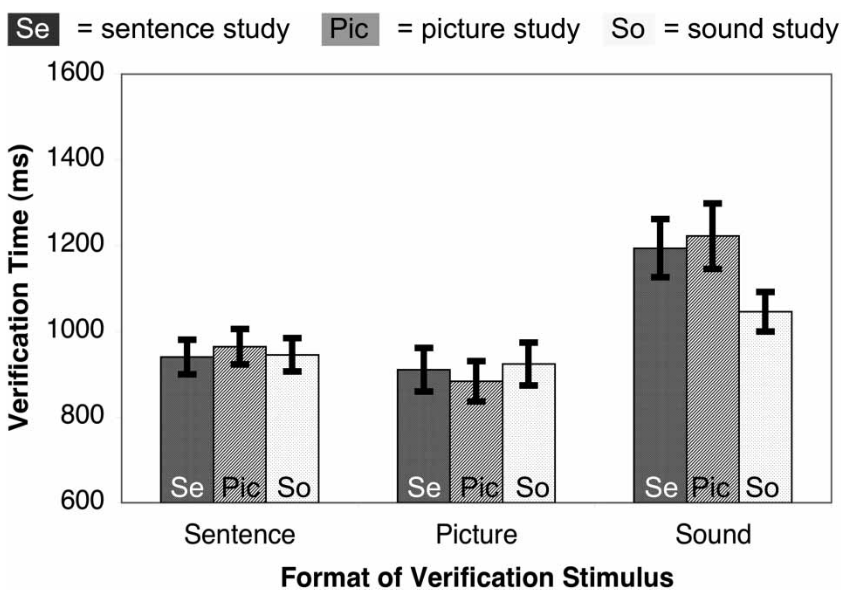

Figure 4. Verification time as a function of study stimulus format and verification stimulus format. Error bars represent *SEM.*

Analysis of percentage correct

A secondary analysis of the percentage of trials correct within conditions was conducted with a repeated measures analysis of variance (ANOVA) with Greenhouse-Geisser corrections for sphericity violations. The assumption of sphericity was violated for the main effect of verification stimulus format, and the interaction of study stimulus format with verification stimulus format, Mauchly's Ws = .41–.83, ps < .05, ϵs = .67–.86. The sphericity assumption held for the main effects of strategy and study stimulus format, the interaction of strategy with study stimulus format, the interaction of strategy with verification stimulus format, and the 3-way interaction, Mauchly's Ws = .25–.96, ps > .05.

Nonsignificant effects included the main effect of strategy, $F < 1.00$, and the main effect of study stimulus format, $F(2, 74) = 1.23$, $p > .05$. Results showed a significant main effect of verification stimulus format, $F(1.71, 63.30) = 10.27$, $p < .001$, $\eta_p^2 = .22$. Pairwise comparisons showed that participants made fewer mistakes when the verification stimulus was a sentence (M = 94.0%, SE = .8), $p < .05$, or a picture (M = 95.6%, SE = .7), $p < .001$, as compared to sounds (M = 92.0%, SE = .12). Results also showed a significant

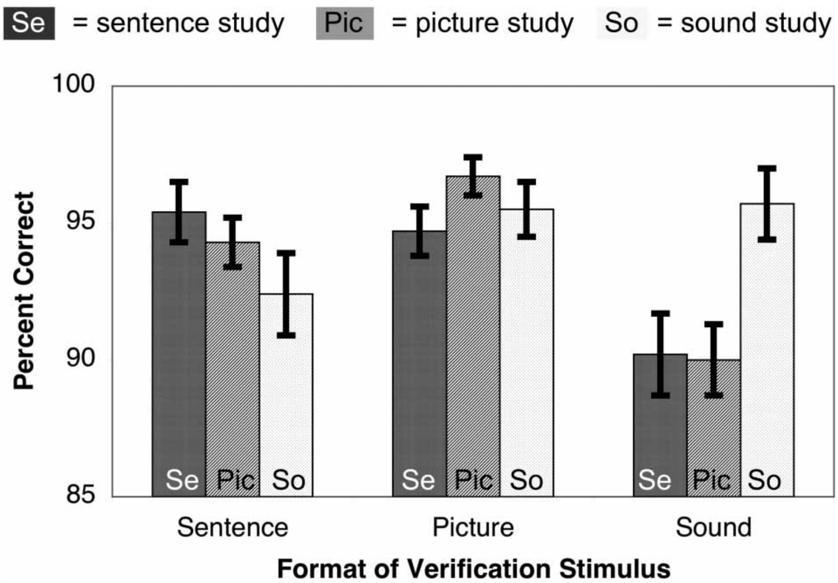

Figure 5. Percentage of correct responses as a function of the study stimulus format and the verification stimulus format. Error bars represent *SEM*.

interaction of study stimulus format with verification stimulus format, $F(2.62, 97.03) = 8.90$, $p < .001$, $\eta_p^2 = .19$. Simple effects analyses at each level of the verification stimulus format showed that when the verification stimulus was a picture (middle three bars of Figure 5), participants made significantly fewer errors if they had studied a picture ($M = 96.7\%$, $SE = .7$) as compared to sentences ($M = 94.7\%$, $SE = .9$), $p < .05$. When the verification stimulus was a sound (right three bars of Figure 5), participants made significantly fewer mistakes if they had studied a sound ($M = 95.7\%$, $SE = 1.3$) as compared to sentences ($M = 90.2\%$, $SE = 1.5$), $p < .001$, or pictures ($M = 90.0\%$, $SE = 1.3$), $p < .001$. All other differences were nonsignificant, ps $= .09$–$.83$. The interaction of strategy with study stimulus format, the interaction of strategy with verification stimulus format, and the three-way interaction were all nonsignificant, Fs < 1.00.

DISCUSSION

Verification times were predicted to be fastest for a given verification stimulus when it matched the participant's encoding strategy. This pattern was confirmed fully for sentence and sound verification stimuli and partially for picture verification stimuli, for which the visual and verbal encoding strategies were equally fast. Further, no congruency effects were expected between the format of the study stimulus and the format of the verification stimulus, because the study stimulus was to be recoded according to the encoding strategy. This pattern was confirmed for both sentence and picture verification stimuli, but facilitation was observed for sound verification stimuli if a sound had been studied.

Results generally offered evidence in support of the hypothesis that, regardless of the external format of a to-be-remembered stimulus, participants could invoke a prescribed strategy to remember a stimulus in working memory. Sentences were verified fastest by participants using a verbal strategy. One of the hallmarks of verbal/propositional encoding is the supplantation of sensory information (e.g., contained in the pictures and sounds) with the verbal code (see Tracy, Roesner, & Kovac, 1988), and the notion that verbal encoding drops sensory qualia of stimuli was generally supported by this result (though with a possible exception when a sound was studied, see below). The successful implementation of verbal encoding is perhaps not surprising, as verbally labelling stimuli is common in cognition (e.g., Colegate & Eriksen, 1970).

When the verification stimulus was a picture, participants responded equally quickly using both visual imagery and verbal encoding. Noordzij et al. (2005) suggested that both the verbal and visual representations of visual percepts are automatically encoded in visual imagery strategies. The appearance of a picture verification stimulus possibly automatically activated an accompanying verbal code. Visual *imagery* did not appear to carry a verbal code in the same way that a visual percept may have activated a verbal code, as participants using the visual imagery strategy were slower to verify sentences as compared to those using the verbal encoding strategy.

When the verification stimulus was a sound, as predicted, participants responded fastest using the auditory imagery strategy. The overall pattern of results for both verification times and accuracy suggested that people were slower and less accurate at deciphering the basic stimulus state of nonspeech auditory stimuli as compared to sentences and pictures, perhaps because nonspeech sounds were an unfamiliar mode for this type of information. Participants' response times and accuracy may have been affected by the specific pitch changes used here, or they may have incurred modality-switching costs (Spence, Nicholls, & Driver, 2001). Another possibility is that auditory imagery was less vivid and useful than visual imagery (Tracy et al., 1988).

Interestingly, a congruency effect was observed when the verification stimulus was a sound; participants were at an advantage for both verification times and accuracy (collapsed across encoding strategies) when they had studied a sound as compared to a sentence or picture (Figures 4 and 5, right 3 bars). This finding may be attributable to a persevering form of auditory sensory memory. Researchers have varied widely in their estimates of the time course of auditory sensory memory (ranging from a few hundred milliseconds up to a few seconds, see Cowan, 1984), but this result suggested that the perceptual qualities of a sound may linger for several seconds following perception, even when the stimulus has been recoded deliberately into a verbal or visual image format.

The current study offered some qualified evidence to suggest that sentences, pictures, and sounds can be flexibly encoded in working memory. Some evidence was provided for the suggestion (Noordzij et al., 2005) that verbal codes are automatically activated during visual *perception*, but such activation was not evident with visual *imagery*. Previous research (Paivio et al., 1989) has suggested that verbal and visuospatial connections may be bidirectional, but our results suggested an asymmetry whereby visual percepts activated accompanying verbal codes but visual imagery did not. Results suggested that the effects of a nonspeech auditory percept linger for some time even despite nonauditory encoding strategies. In general, this study suggested that the mode of the perceptual stimulus is no more important, and may be less important, than the encoding strategy for remembering and rehearsal in working memory.

Though Baddeley and Logie (1992) argued for the storage component of verbal working memory as the explanatory mechanism of auditory imagery, the implications of this hypothesis remain unresolved in the literature. For example, from this perspective the concurrent processing of speech and nonspeech sounds in working memory should interfere, yet data to this effect are equivocal (for a review, see Smith, Reisberg, & Wilson, 1992). Further, the flexibility of encoding and the consequences of recoding percepts in working memory (e.g., translating words to images and sounds and vice versa) are not well understood (but see Paivio et al., 1989). Research on the role of auditory imagery in cognition and the recoding of percepts in working memory could clarify gaps in existing theory and inform the best practices for presenting information in practical applications.

Auditory imagery may have important differences with verbal and visuospatial processes in working memory. The extent to which auditory imagery does or does not require articulation (a verbal, domain-specific processing structure) remains unclear. Researchers have overwhelmingly embraced the premise of separate representational processing systems for verbal and visuospatial information (e.g., Baddeley & Logie, 1992; Paivio et al., 1989; Wickens, 2002). This experiment contributes to an emerging body of evidence that the dual-process dichotomy may omit a limited set of other plausible independent working memory processes such as auditory imagery, and also that existing theories may underestimate the flexibility of encoding processes by unnecessarily linking external stimulus modalities with determinate processing formats in working memory.

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APPENDIX: EXAMPLE ENCODING INSTRUCTIONS

The instructions below are the verbatim encoding instructions for the auditory imagery strategy. The visual imagery and verbal strategy instructions followed parallel forms but substituted details relevant to those strategies, respectively.

For this block, you must use the sound strategy. Regardless of whether Stimulus A is a sentence, picture, or sound, you must turn it into a sound in your mind. Use this sound for increasing price: [increasing price sound stimulus played]*, and this sound for decreasing price:* [decreasing sound stimulus played]. *Don't press "Z" or "?" to leave Stimulus A until you have a vivid sound to represent the stock price in your pitch memory. Keep rehearsing this sound in your mind* (during the grey blank screen) *until Stimulus B appears. You should imagine the sound playing through your headphones during this time. Summary of instructions for the sound strategy: (1) Turn Stimulus A into either the increasing or decreasing sound in your mind. Don't continue until you can hear the sound in your mind, even if the actual stimulus is a sentence or picture. (2) Press "Z" or "?" to continue. During the brief wait with the grey screen, you should be hearing the sound in your pitch memory. Imagine the sound playing in the headphones. (3) Decide if the sound in your mind matches the state of the stock* (increasing or decreasing) *for Stimulus B and make a response. Please get the experimenter now. The experimenter will help you start this block!* [The experimenter reiterated the instructions to the participant and checked with the participant to confirm that the participant understood the instructions.] *It is very important that you follow these exact instructions on every trial until further notice!*