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An online task for contrasting auditory processing in the verbal and nonverbal domains and norms for younger and older adults

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Abstract

Contrasting linguistic and non-linguistic processing has been of interest to many researchers with different scientific, theoretical or clinical questions. However, previous work on this type of comparative analysis and experimentation has been limited. In particular, little is known about the differences and similarities between the perceptual, cognitive and neural processing of nonverbal environmental sounds compared to speech sounds. We developed a new online measure with the aim of contrasting verbal and nonverbal processing in the auditory modality, that can be administered to subjects from different clinical, neurological, or socio-cultural groups. This is an online task of sound to picture matching, where the sounds are either environmental sounds or their linguistic equivalents, which is controlled for potential task and item confounds across the two sound types. Here we describe the design and development of our measure and report norming data for healthy subjects from two different adult age groups: Younger adults (aged 18-24) and older adults (aged 54-78). We also outline other populations to which the test has been or is being administered. In addition to the results reported here, the test can be useful to other researchers who are interested in systematically contrasting verbal and nonverbal auditory processing in other populations.

Introduction

An environmental sound can be defined as a sound that is produced by a real event; a sound takes on meaning due to the causal relationship with that event (Ballas & Howard, 1987). Unlike linguistic sounds, which are relatively arbitrary labels assigned to objects, events and concepts, environmental sounds bear a more iconic correspondence to the object or event with which they are associated.

Most humans can easily comprehend both linguistic and environmental sounds, and can usually identify the referents in either case. However, the similarities and differences in the cognitive and neural processing of these two types of sounds are not well-understood.

Environmental sounds share quite a few perceptual and informational features with language (Gygi, 2001), thus making them useful in exploring possible links between verbal and nonverbal auditory processing. Indeed, several studies suggest that environmental sounds may be processed similarly to linguistic stimuli. Like language processing, there are frequency and priming effects in processing environmental sounds: i.e., commonly encountered sounds are more easily identified and hearing a sound can facilitate the identification of a subsequent sound that is related (Ballas, 1993). Such results have been supported by neuroimaging studies as well. For instance, an event-related potential (ERP) study found that conceptual relationships between spoken words and environmental sounds influence the processing of both types of stimuli (Van Petten & Rheinfelder, 1995). Another ERP study concluded that similar mechanisms might be involved in processing words and environmental sounds, because both types of stimuli show differential brain activity as a function of familiarity (Cycowicz & Friedman, 1998). Functional neuroimaging studies of human auditory processing have shown that regions in the human temporal lobes often associated with language are more active for certain types of sounds, but it is not yet clear whether these effects reflect division based on type (e.g. music vs. speech), semantic content, or spatial and temporal complexity of the sound stimuli used (Binder, Frost, Hammeke, Bellgowan, Springer, Kaufman, et al., 2000). Functional activation related to environmental sounds has only been examined in a few studies so far (Adams & Janata, 2002; Dick, Saygin, Pitzalis, Galati, Bentrovato, D'Amico, et al., 2004; Humphries, Buchsbaum & Hickok, 2001; Lewis, Wightman, Junion Dienger & DeYoe, 2001; Maeder, Meuli, Adriani, Bellmann, Fornari, Thiran, et al., 2001). In these studies, contrasts with linguistic sounds were not always carried out, however, sounds were observed to activate middle and superior temporal brain areas that have been associated with language-processing in earlier studies (e.g., Binder, 1997; Wise, Chollet, Hadar, Friston, Hoffner & Frackowiak, 1991).

Environmental sound processing has also been studied in clinical populations such as in patients with autism (van Lancker, Cornelius, Kreiman, Tonick, Tanguay & Schulman, 1988), Landau-Kleffner syndrome (Korkman, Granstrom, Appelqvist, & Liukkonen, 1998), and Down syndrome (Marcell, Busby, Mansker, & Whelan, 1998). However, the bulk of the work has centered around adults with brain lesions. Researchers have long used data from patients with language deficits due to brain damage (aphasia) to explore the mechanisms that guide the processing of language by the human brain. Similarly, studies of *auditory agnosia* (deficits in auditory comprehension despite normal hearing) may shed light on environmental sound processing and its neural bases. Most reported cases of auditory agnosia are associated with bilateral damage involving auditory cortex, but subcortical lesions can also cause the deficit (e.g., Kazui, Naritomi, Sawada, Inoue & Okuda, 1990). Less frequently, unilateral left and right hemisphere lesions have also been reported to cause different kinds of auditory agnosia (see Clarke, Bellmann, Meuli, Assal, & Steck, 2000; Saygin, 2001; Vignolo, 1982 for reviews). A clear picture does not emerge from case study findings, both because auditory agnosia is a rare disorder and because there were no normalized tests administered to all the patients.

Experimental studies of environmental sound processing performed with larger groups of neurological patients have provided better insights. To our knowledge, Vignolo, Spinnler and Faglioni were the first to report disturbances of environmental sound recognition due to unilateral brain damage (Faglioni, Spinnler, & Vignolo, 1969; Spinnler and Vignolo, 1966; Vignolo, 1982). They observed that compared to normal controls, right hemisphere-damaged (RHD) patients performed significantly worse on *perceptual* tests involving environmental sounds while left hemisphere-damaged (LHD) patients performed significantly worse on *associative/semantic* tests. Later, Varney (1980) used environmental sounds in examining verbal and nonverbal comprehension deficits in a group of aphasic patients (i.e., patients with diagnosed *language* deficits). He found that defects in environmental sound recognition were seen only in subjects with impaired verbal comprehension, and all the aphasics with intact verbal comprehension performed well on sound recognition. There were, however, aphasics who were impaired in verbal comprehension, but not in sound recognition. More recently, Schnider, Benson, Alexander & Schnider-Klaus (1994) observed that both LHD and RHD patients performed significantly worse than a group of normal controls on an environmental sound recognition test. Here, LHD patients made semantically-based errors (i.e., when they made errors, they picked a distracter item which was semantically related to the target) while RHD patients and control subjects made almost exclusively acoustic errors. Lesion-behavior correlations showed that LHD patients with impaired environmental sound recognition tended to have damage to the posterior superior temporal gyrus (pSTG) and the inferior parietal lobe.

While these studies shed more light on the brain mechanisms behind environmental sound processing, they do not provide a complete picture of the relationship between verbal and nonverbal auditory comprehension. For example, several studies did not test language comprehension in relation to sound processing, instead focusing on different questions: e.g., Clarke et al (1996, 2000) tested patients on environmental sound identification but they were exploring similarities and differences between sound identification and sound localization so did not test language comprehension. Those studies that did have an explicit comparison of performance between verbal and nonverbal domains (Schnider et al., 1994; Varney, 1980), did not attempt to control for certain task-related factors, such as stimulus frequency, stimulus identifiability, and the relationship between the auditory and visual stimuli. Furthermore, none of these studies used online measures such as reaction time, and therefore could not make use of information that the time course of processing may provide.

Here we describe an online experiment that explicitly aimed at contrasting environmental sound and language processing. Using the results of a norming study as a basis for stimuli selection and/or creation (see description below), we designed a 2-alternative sound-picture matching task that allows for within-subject comparison of performance on environmental sound and language processing while tightly controlling for possible task- and stimulus-related confounds. We cross this Domain contrast (environmental sounds vs. speech sounds) with a ‘processing-load’ factor, namely Semantic Relatedness - a manipulation that has revealed interesting differences in patient subgroups, as discussed above.

This experiment can be administered to a wide range of patient populations, from early ages to late adulthood. In our own laboratory, we have administered it to patients with brain damage due to stroke (Saygin, 2001; Saygin, Dick, Wilson, Dronkers & Bates, 2003) as well as normal subjects using functional magnetic resonance imaging (Dick et al, 2004). The test is currently being administered on neurologically and/or language impaired, as well as normally developing children. In addition to the norming results we present here, the experimental stimuli will be made available upon request to researchers who wish to study or contrast verbal and nonverbal auditory processing in different subject populations.

Methods

Preliminary Experiment:

Aims: A pilot study on young adult subjects with no hearing disorders was carried out to (a) test a large set of candidate sound stimuli for identifiability, and (b) extract verbal labels (including at least a noun and a verb) to be used in the linguistic sound processing condition of the main experiment.

Participants: Participants were 31 undergraduate and graduate students at the University of California, San Diego, aged 18-31. All subjects were native speakers of English, had normal or corrected to normal vision and normal hearing. They were given a handedness-assessment questionnaire (Oldfield, 1971), and a brief language history questionnaire; these are routinely administered at our facility prior to experiments. We did not exclude any subjects from the present study based on foreign language exposure or handedness.

Materials: The sound stimuli were taken from various digital sound effect libraries on the Internet. The sampling rate of the sounds was 44.1 kHz, with 16-bit quantization.

Procedure: Subjects were seated in a small room, in front of a computer. The experiment was run on Macintosh computers, and PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993) was used to deliver stimuli. A PsyScope button box was used to collect the responses. Sound stimuli were presented through Optimus Pro 50MX headphones. Following the procedure introduced by Ballas (1993), we asked subjects to listen to a large number of environmental sounds and to press a button as soon as they believed they had identified the source of each sound. They then provided a verbal identification of the sound, being instructed to provide both a noun and a verb (e.g., dog barking, engine running). They were specifically asked not to press the button unless they had identified the source of the sound, and to react as quickly as they could when they identified the sound.

We collected a noun and a verb response specifically because we wanted to use phrases which contain both a noun and a verb in the main experiment (see below) as sound descriptors. In pilot studies, we observed that when subjects were asked to name sounds “free form”, without being instructed to use a noun or a verb specifically, some tended to use nouns for a portion of the items (e.g., some subjects would say “dog” to name the sound of a dog barking). But we noted that single nouns often would not be the best descriptors for a relatively large set of environmental sounds, as for certain sets of sounds, subjects tended to describe the sound using a verb (e.g., they would say, “coughing”, or “someone coughing”, but not “a cough”). However, single verbs, particularly very frequently used transitive verbs, do not differentiate between the objects of the actions in some cases. Consider the verb "play" – playing the piano, violin, trumpet, flute all make sounds that are different. One could add to these playing golf, basketball, baseball, etc. Yet "playing" would describe them all and not differentiate between them. Thus nouns *or* verbs in isolation are insufficient linguistic descriptors for many environmental sounds. Hence subjects in the present study were instructed to provide at least a noun and a verb for each sound that they heard (occasionally subjects provided considerably more detail in the form of prepositional phrases, adverbs, and so on).

Subjects completed a practice block of 8 trials and an experimental block of 236 trials. The experimenter initiated each trial by pressing a key on a keyboard, then recorded all verbal responses as well as information such as erroneous button presses.

Analysis and results: The responses were analyzed for accuracy, defined as follows. Verbal responses were coded by two independent raters. Each response was given a score between 0 and 2, where 0 denoted a wrong response (or no response), 1 denoted a response that was not exactly correct but has common elements with the correct response, and 2 denoted a correct response. The sum over all 31 subjects of such scores was used as an indicator of how hard the subjects found that sound to identify with the lowest possible sum being 0 (all subjects responding incorrectly) and highest possible sum being 62 (all subjects responding correctly). For simplicity, each sum was then divided by 6.2, converting it into an identifiability score ranging from 0 (low identifiability) to 10 (high identifiability). The two raters had high agreement on their scoring; the correlation between the raters was $r = 0.84$. The mean identifiability score from the two raters for all sounds was 8.25 (st. dev. = 2.42, min = 0, max = 10)

Reaction times were analyzed only for valid and correct trials. A total of 774 of 7316 responses were excluded from reaction time analyses (collected from the summed over 31 subjects on the 236 items).The following method was devised to count only RTs to valid and correct responses. First of all, responses involving accidental button presses, multiple verbal labels (where the subject changed his or her mind about the correct label of an item), or outright errors were excluded based on experimenters' notes and the verbal responses. Items for which there was no button press recorded by the experimental computer were also excluded. The remaining responses were categorized as valid, and the corresponding RTs were used in further analyses according to the following criteria: (a) the response should be classified as correct by at least one rater, and (b) the response should not be classified as incorrect by either rater. Therefore the coding patterns allowable were Rater A=2, Rater B=2; Rater A=1, Rater B=2, or Rater A=2, Rater B=1. This scheme not only eliminated incorrect responses from the RT analysis, but also eliminated using items on which the two raters differed in terms of absolute correctness (0 and 2). After the elimination of incorrect responses using this scheme, there were 5887 trials on which the response was considered correct and the RT was considered valid.

The mean RT was 1813 msec with a standard deviation of 811 msec. There was a significant relationship between RTs and identifiability scores: Easily identified items tended to have shorter RTs. The result was significant for the total scores reported by both raters. (For Rater A, $p<0.0001$, $r^2=0.31$; for Rater B, $p<0.0001$, $r^2=0.20$). When the items were categorized into groups of animal, human, machine, music, event and alarm/alert sounds, we saw that omnibus ANOVA with RT as dependent variable was significant ($p<0.0001$). Event (mean RT=2087 msec, std. dev=883 msec) and machine (mean RT=1961 msec, std. dev=924 msec) sounds tended to be slower to identify than other categories. Human (mean RT=1270 msec, std. dev.=454 msec) and alarm/alert (mean RT=1386 msec, std. dev=606 msec) sounds were faster identified than others. Animal and music sounds had intermediate mean RTs (1535 and 1770 msecs, with std. dev.=536 and 617 msecs, respectively). For a more detailed discussion of environmental sound naming as well as possible category effects the reader is referred to (Gygi, 2001; Marcell, Borrela, Greene, Kerr, & Rogers, 2000).

Main Experiment

Participants: 25 younger and 20 older adults were tested. Younger adults were UCSD students aged 18-24 (mean = 20.5, std. dev = 1.6) and participated in exchange for course credit. Older adults were 20 members of the community, aged 54-78 (median =68, mean = 66, std. dev = 8.4) and were paid for their participation. The older subjects had been recruited as control subjects for experiments carried out as part of the International Aphasia Project at the Center for Research in Language. All participants were native speakers of American English, had normal or corrected to normal vision, and no known neurological or psychiatric conditions. They were tested for hearing impairment with a standard questionnaire – subjects with known or suspected hearing loss were not allowed to participate. Participants gave informed consent to participate in the study, which was approved by the UCSD Human Research Protections Program. Data from one older adult was excluded from all analyses because of talkativeness and inattention to the task.

Materials and design: The experiment utilized three kinds of stimuli: Black-and-white line drawings, nonverbal sounds, and speech sounds.

The visual stimuli were 10.6 cm x 10.6 cm digitized drawings culled from normed picture databases (Bates, D’Amico, Jacobsen, Szekely, Andonova, Devescovi, et al., 2003; Szekely, D'Amico, Devescovi, Federmeier, Herron, Iyer, et al, in press).

The nonverbal sound stimuli were selected from among the stimuli normed in the preliminary experiment. Selection criteria included identifiability (moderate to high), inter-rater reliability for identifiability, imageability (identifiability/availability of picture), and reaction time (for sounds that had multiple exemplars in the norming study, the item with the shorter reaction time was selected, unless there was a conflict with identifiability). The sampling rate of the sounds was 44.1 kHz, with 16-bit quantization. Appendix A contains a list of the sounds selected for use in the experiment; for each sound we report its identifiability score, the mean reaction time for correct identification, and its duration.

The language stimuli were phrases determined based on the most common labels provided by the subjects in the preliminary experiment. In examining subjects' correct responses, we found that the most commonly reported noun and verb were put together most often in 'NP + V-ing (+Obj)' constructions (e.g., "cow mooing", "water boiling", "tractor engine running", "someone eating an apple"). Thus, we used this syntactic frame for constructing all the linguistic phrases. For a small subset of sounds, the responses obtained in the preliminary study tended to be passive phrases (e.g., "piano being played", "baseball being hit"). In order to retain continuity across the experiment, these were converted to active phrases that resemble the rest of the verbal stimuli (e.g., "piano playing", "someone hitting a baseball"). Note that for musical instruments we systematically used the phrase "<instrument> playing"; this was a common construction produced in the preliminary study and these descriptions fit the pictures well. All phrases were read by a North American 38-year-old male speaker, and were digitally recorded with a 44.1 kHz sampling rate with 16-bit quantization).

<--- FIGURE 1 HERE --->

As noted above, subjects' task was to match each verbal or environmental sound to one of two pictures. We used a fully crossed 2-within x 1-between design, with Domain (Verbal/Nonverbal) and Visual Distracter Type (Distracter related to target/Distracter unrelated to target) as within-subject factors, and Subject Group as the between-subjects factor. For example, for the target "cow", the semantically related visual distracter was "sheep" and the unrelated distracter was "violin". The target "cow" appeared four times, twice with verbal sound stimuli (the phrase "cow mooing"), twice with nonverbal stimuli (the sound of a cow mooing), twice with "sheep" as the visual distracter, and twice with "violin" as the distracter. Figure 1 summarizes these four trial types. There were 45 pictures and sounds that acted as targets and related and unrelated distracters, giving rise to 45 triplets such as "cow-sheep-violin". The full list of such triplets used in the experiment are available in Appendix B. Note also that each list was fully counterbalanced such that each target picture also appeared as distracters in other trials, i.e., “cow” was not always a target, but was also a semantically related distracter for the target “horse” and a semantically unrelated distracter for the target “sing” (see Appendix B). A total of 180 trials were administered.

Twenty quasi-random orders of the list were rotated among the subjects. A potential concern was whether the sounds previously encountered in the experiment would have a priming effect on subsequent items. Findings from an environmental sound repetition priming study indicated that prior encoding of target sounds together with their associated names facilitated subsequent identification of sound stems, whereas prior exposure to the names alone in the absence of the environmental sounds did not prime subsequent sound identification (Chiu & Schacter, 1995). Another study found that identification of an environmental sound was facilitated by prior presentation of the same sound, but not by prior presentation of a spoken label; conversely, spoken word identification is facilitated by previous presentation of the same word, but not when the word had been used to label an environmental sound that the subjects heard before (Stuart & Jones, 1995). In order to preclude any possible order effects, we used a large number of different list orders pseudorandomly assigned over subjects.

In order to verify that semantically related and unrelated distracters were appropriately assigned, we made use of the measure *latent semantic analysis,* henceforth LSA. This is a computational index of semantic relatedness that tends to assign larger numbers to more related pairs of word sets. (LSA can be used freely at http://lsa.colorado.edu; the reader is referred to the web site and Landauer, Foltz, & Laham, (1998) for background information).

Each list was balanced such that (a) the related distracter was more similar to the target than the unrelated distracter was to the target, as measured by a higher LSA index, and (b) the LSA index for the relationship between the target and the related distracter was higher than the LSA index for the relationship between the related and unrelated distracters. Across all 45 items, the average LSA index for semantically related pairs was 0.36 (st. dev. = 0.21), for unrelated pairs it was 0.04 (st. dev. = 0.05), a highly significant difference (p<0.0001).

Procedure: The experiment was run on Apple Macintosh PowerBook 3400c computers using the PsyScope experimental driver (Cohen et al., 1993).[1] Participants sat in front of a VGA monitor, YST-M7 speakers were placed on each side, and a standard PsyScope button box was used to collect their responses. They were given instructions, then asked to complete a practice session of 6 trials. The instructions and practice session were repeated if the subject had a problem comprehending or performing the task.

The experimental block consisted of 180 experimenter-advanced trials. In each trial, subjects were presented with a two picture display on the screen. After 1000 msec, the sound stimulus was presented through the speakers. This delay was introduced so as to increase the likelihood of subjects' response latencies being related to the processing of auditory input, rather than relating to parsing of visual scenes. Subjects used a PsyScope button box to indicate which of the two pictures the sound matched (picture presented on the left side of the screen = leftmost button, picture presented on the right side of the screen = rightmost button). The picture selected by the subject remained highlighted until the end of the trial. Reaction time and accuracy were recorded for each trial. Subjects were observed as they performed the task to make sure that they remained alert and attentive, and were asked at intervals whether they needed a break. The nature of the errors the subjects made was noted, along with any comments the subjects made. Particular attention was paid to the subject's immediate awareness of the error, as indicated by an overt verbal or physical response. Feedback was provided as often as considered necessary to keep the subject involved, or approximately once every twenty trials. Feedback was never negative, but was non-committal as to the accuracy of the response to the preceding trial (e.g., "you are doing great so far", "we are halfway through", "going good").

Results and Discussion

We first summarize results within each age group alone, and then present results collapsed over all groups. Tables 1 and 2 provide the means and standard deviations for accuracy and RT measures associated with the 4 conditions (verbal vs. nonverbal sound, related vs. unrelated distracter) for younger and older adults. These norms may be used to assess the performance of future subjects performing this task, and to explore any relative differences in performance profiles across the two domains and the two difficulty levels for different subject populations. The results of the analyses are also depicted in Figures 2 and 3. In Appendix C, we also present some supplementary analyses on a subset of the stimulus items that are matched for position of disambiguating information in the linguistic domain.

<TABLE 1 AND TABLE 2 ABOUT HERE>
<FIGURE 2 AND FIGURE 3 ABOUT HERE >

Younger Adults, Accuracy: Here, a 2-within-subject ANOVA revealed a main effect of Domain (verbal vs. nonverbal) ($F1(1,24)=12.999$, $p=0.0014$; $F2(1,44)=7.629$, $p=0.0084$) and Distracter Type (related vs. unrelated) ($F1(1,24)=19.167$, $p=0.0002$; $F2(1,44)=7.665$, $p=0.0082$). where subjects made more errors in the nonverbal domain than in the verbal domain, and more errors in the related distracter condition than in the unrelated distracter condition. The interaction of Domain and Distracter Type reached significance, but only over subjects ($F1(1,24)=5.723$, $p=0.0249$). This interaction suggests that for these subjects, distracter type may have more impact on errors in the nonverbal trials than it does in the verbal trials. Results of post-hoc t-tests suggested that it is the semantically related distracter condition that drives the main effect of Domain, as the means for the unrelated distracter trials did not differ reliably ($p=0.2$), while in the related distracter condition, the means were significantly different ($p=0.01$).

Younger Adults, Reaction Times: Reaction time (RT) data were analyzed using only trials with correct responses. As with accuracy, there was a main effect of Domain ($F1(1,24)=169.966$, $p<0.0001$; $F2(1,44)=29.749$, $p<0.0001$) and Distracter Type ($F1(1,24)=170.447$, $p<0.0001$; $F2(1,44)=62.460$, $p<0.0001$). Interestingly, the effect of Domain was driven by subjects' faster response times in the nonverbal condition than in the verbal condition, the converse of the pattern observed in the accuracy data. The effect of Distracter Type on reaction times followed that of accuracy, where related distracters slowed responses relative to unrelated distracters, just as they negatively affected accuracy. The Domain by Distracter Type interaction was significant ($F1(1,24)=17.863$, $p=0.0003$; $F2(1,44)=5.966$, $p=0.0187$). As with the accuracy data, the effect of distracters was more pronounced for the nonverbal condition.

In summary, for the stimuli set used in this experiment, younger adults identified the sound stimuli slightly faster but slightly less accurately than the verbal stimuli . There was a robust effect of Distracter Type, with related distracters reducing accuracy and slowing reaction time, especially in the nonverbal domain. There seems to be a slight trade-off between speed and accuracy, but given the high levels of accuracy across all conditions, any strong conclusions would be premature.

Older Adults, Accuracy: The pattern of results here followed those of the younger adults. There was a main effect of Domain (verbal vs. nonverbal) ($F1(1,18)=7.773$, $p=0.0121$; $F2(1,44)=4.004$, $p=0.0516$) and Distracter Type (related vs. unrelated) ($F1(1,18)=47.368$, $p=0.0004$; $F2(1,44)=7.015$, $p=0.0112$). Just like younger adults, older subjects made more errors in the nonverbal domain than in the verbal domain, and more errors in the related distracter condition than in the unrelated distracter condition. The interaction of Domain and Distracter Type was not significant, with only a marginal effect over subjects ($F1(1,18)=3.513$, $p=0.0772$) and non-significant over items.

Older Adults, Reaction Times: As with younger subjects, there was a main effect of Domain ($F1(1,24)=169.966$, $p<0.0001$; $F2(1,44)=5.518$, $p<0.0234$) and Distracter Type ($F1(1,24)=170.447$, $p<0.0001$; $F2(1,44)=66.205$, $p<0.0001$). Older adults were faster in the nonverbal condition than in the verbal condition, and again, related distracters slowed down responses, with the effect more pronounced in the nonverbal domain. The Domain by Distracter Type interaction was significant ($F1(1,24)=17.86$, $p=0.0003$; $F2(1,44)=16.761$, $p=0.0002$), where the effect of distracters was more pronounced in the nonverbal condition.

Summary of results: Both younger and older adults made more errors in the nonverbal condition, but when they responded correctly, were faster to respond to the nonverbal sounds. However, given the high accuracy levels, we do not wish to interpret this as a reliable speed-accuracy trade-off effect. There was a reliable effect of Distracter Type for both subject groups and both dependent variables, where related distracters were harder to process in both verbal and nonverbal domains. Interestingly, we also observed that the effect of distracters was somewhat more pronounced in the nonverbal condition.

Below we report analyses that compare the two age groups with each other; this serves both to demonstrate how processing of verbal and nonverbal sounds for meaning changes with advancing age, as well as how this test may be used in comparing different subject populations as they perform in the two domains.

When all subjects were analyzed together, the main effects of Domain and Distracter Type remained significant for both accuracy and RT ($p<0.001$ for all Fs). Overall, subjects were significantly faster but slightly less accurate on the nonverbal condition compared to the verbal condition, and they were significantly faster and more accurate on the unrelated Distracter condition compared to the related Distracter condition. There was no main effect of Group on accuracy: older and younger subjects successfully responded to a similar number of items. Not surprisingly though, there was a main effect of Group for RT, with the younger subjects performing faster overall ($F1(1,42)=16.059$, $p=0.0002$; $F2(1,44)=382.852$, $p<0.0001$). The interaction of Group by Distracter Type over RT reached significance ($F1(1,42)=4.401$, $p=0.0420$; $F2(1,44)=5.290$, $p=0.0262$), with older adults slightly more affected by Distracter Type. (This interaction was not significant for accuracy). Interestingly, there was an interaction of age with Domain: Relative to older adults, younger adults were much faster on non-verbal than on verbal trials ($F1(1,42)=18.286$, $p=0.0001$; $F2(1,44)=25.955$, $p<0.0001$). Once again, this interaction was not found in the accuracy results. For RT, the three way interaction of Group by Domain by Distracter Type ($F1(1,42)=7.756$, $p=0.0080$; $F2(1,44)=4.068$, $p<0.0498$) was significant; this higher-order interaction appeared to be driven by older adults' greater susceptibility to related distracters while processing environmental sounds. For the younger group, the difference between the mean RT for related verbal items and that for nonverbal items was 165 msec, for older subjects this difference was only 32 msec; the same differences for the unrelated distracter condition were 238 msec and 246 msec respectively.

Accuracy results are depicted in Figure 2 split by subject group. None of the comparisons between these groups reached significance. For RT, the results are similarly depicted in Figure 3. Younger subjects were significantly faster in all four conditions (all $p<0.02$, Bonferroni corrected).

Overall, age seemed to affect only response latencies, with accuracy levels comparable across groups and conditions. Younger adults were faster to respond in all conditions, while normal aging appeared to affect non-verbal processing more than its verbal analogue.

We should emphasize that the faster responses to the nonverbal sounds observed in both groups does not mean that people process nonverbal sounds more easily than speech sounds. Similarly, the higher levels off accuracy for verbal sounds does not mean that people are better at processing these sounds. These mean accuracies and response latencies are better seen as being due to the nature of the stimuli used in this experiment. On the other hand, these response latencies do shed light on another issue: The idea that linguistic processing could be mediating the identification and/or processing of environmental sound has been proposed in discussions of previous work with these kinds of stimuli (as evidenced by discussion and interpretation of data in many studies cited here, as well as the position argued by Bartlett, 1977, for instance). For both of the populations we tested, environmental sounds were processed faster than their linguistic labels, thus suggesting that linguistic mediation is likely not the strategy used in processing these sounds. In fact, we recently put this hypothesis to test explicitly in a related study, verifying that covert naming of environmental sounds exerts an additional processing load above and beyond that used for recognition alone (Dick, Bussiere, & Saygin, 2002).

On the other hand, the distracter condition has significant interactions with sound type: by varying the difficulty of distracting items, we can manipulate performance in the nonverbal domain more than the performance in the verbal domain. This may be an indication that performance on nonverbal sounds is more susceptible to increased processing load. Furthermore, the expected processing slowdown that accompanies aging also affects nonverbal processing more than it affects verbal processing suggesting that the nonverbal processing system may indeed be slightly more vulnerable.

Despite these cross-domain differences in group performance, there did seem to be some underlying semantic processing load underlying subjects’ performance, in that there was a marginally significant correlation between RTs for linguistic and non-linguistic items ($r=.27$, $p = 0.07$).

Conclusion

While contrasting verbal and nonverbal sound processing is a potentially interesting research venue, there were few studies in the literature that actually attempted to address this question. We developed an online task that allows contrasting these two kinds of processing and reported norms for healthy native English speakers. The task has several potential applications to different populations and some that have already been carried out: We have administered this test to adults with unilateral brain damage (Saygin, 2001) and carried out lesion-mapping to find out more about the neural tissue in the left hemisphere that is most crucial for successfully processing these two kinds of sounds (Saygin, et al., 2003). We have also used the paradigm in identifying an unusual case of auditory agnosia (Saygin & Moineau, 2002). More recently, we have analyzed functional activation in healthy controls performing this task using fMRI (Dick, et al, 2004). Testing is underway to explore processing of these sounds at different stages of normal development, as well as performance profiles in children with focal brain lesions, epileptic aphasia, or language impairment. Furthermore, parallel studies (for both the preliminary and the main experiment) are now being carried out in Italian and Chinese to test the cross-linguistic and cross-cultural generalizability of the results reported here. Once culture and language specific aspects of sound processing are taken into account, environmental sounds can serve as a relatively culture-free baseline for neuroimaging studies of language processing in normals, and for cross-linguistic comparisons of symptoms in adults and children with language disorders.

The experimental program and stimuli are available for download for research purposes on the World Wide Web at http://crl.ucsd.edu/~saygin/soundspics.html. Combined with the norming results reported here, the stimuli may be used in contrasting verbal and nonverbal auditory processing in subjects from other clinical, neurological, or socio-cultural backgrounds.

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Appendix A

This appendix provides further detail on the environmental sound stimuli used in the main experiment. The verbal label and the identification statistics reported here are taken from the preliminary experiment.

<TABLE A1 HERE>

Appendix B

Items used in the main experiment are provided below. 45 triplets were used. The target picture appeared with the related and unrelated distracters in separate trials. Each distracter appears as a target picture and as the other kind of distracter itself such that the list is always fully balanced. More detailed about the pictures used and the naming data on these pictures are presented in Bates et al. (2003).

<TABLE B1 HERE>

Appendix C

As was mentioned in the introduction, it is important to match semantic content in experiments contrasting linguistic processing and nonlinguistic processing; however, this has not been addressed satisfactorily in prior studies on speech and environmental sound processing. As described in the methods of the preliminary norming experiment, one of the goals of this study was to obtain verbal labels based on the available semantic content for each environmental sound using a systematic procedure. As a result of this process, while we have attempted to match semantic content as closely as possible between our verbal and nonverbal stimuli, we also inevitably introduce some variability into our linguistic item set.

In the actual set of test items, a significant source of item variability was the following: While most items began with the disambiguating word (e.g. "*cow* mooing"), in a smaller subset of the items the disambiguating cue appeared later (e.g. "someone playing *golf*"). 11 of the 45 linguistic items started with "someone ..." and thus were disambiguated later in the trial. (These items are listed in Appendix A). Two additional items possibly falling into this late-disambiguating class were "woman singing" and "woman laughing"; however, in both of these cases, the distracter picture did not depict a female and hence the word "woman" was actually a valid cue. It is worth reiterating that the 'someone …' items were included in order to remain faithful to the average description provided by our subjects in the norming study,

In order to verify that the late-disambiguating items were not skewing our results, we contrasted the RTs that did or did not begin with 'someone …'. Not surprisingly, the eleven linguistic sounds beginning with the ambiguous "someone..." were responded to slower than the 34 linguistic sounds that did not begin with "someone...", where mean RTs were 1282 vs. 997 msec, respectively, $p<0.0001$. However, the mean RT differences between the early- and late-disambiguating items did not appear to contribute to the overall results. When all analyses were re-run while excluding 'someone…' items, all experimental effects were just as before, with only a slight decrease in statistical significance (most likely due to the decreased power inherent in a smaller sample size). Results from analyses excluding all 'someone…' items were as follows: Older adults were significantly slower compared with younger subjects, as evidenced by a main effect of Group ($F1(1,42) = 16.529$, $p = 0.0002$; $F2(1,33) = 352.997$, $p < 0.0001$). As with the full set of items there was a main effect of Domain, where linguistic sounds were overall responded to slower than nonlinguistic sounds ($F1(1,42)=72.028$, $p<0.0001$; $F2(1,33)=8.341$, $p = 0.006$). And as before, Distracter Type had a significant effect on reaction time ($F1(1,42) = 318.738$; $p< 0.0001$; F2(1,33) =

51.912, $p<0.0001$). There were also no differences in interactions: There was a significant Group by Sound Type interaction ($F1(1,42) = 18.860$, $p<0.0001$; $F2(1,33) = 24.075$, $p<0.0001$), where younger participants were relatively faster on nonverbal trials. Distracter type significantly interacted with age, as before ($F1(1,42) = 5.704$, $p=0.0215$; $F2(1,33) = 5.511$, $p=0.0250$), where effects were larger for older subjects. Finally, the three-way interaction of Group by Domain by Distracter Type was also significant ($F1(1,42) = 6.666$, $p=0.0134$) although because of decreased statistical power the effect was only marginal now for items analyses, ($F2(1,33) = 3.090$, $p=0.0881$). As before, this interaction reflects the older subjects' greater vulnerability to the effects of related distracters while processing environmental sounds.

<TABLES C1 AND C2 ABOUT HERE>

In short, inclusion (or removal) of these late-disambiguating items does not appear to affect the experimental factors in question. Because of this, we recommend that all 45 items be used, both for reasons of added statistical power, and proper counterbalancing of items. In case investigators wish to use the subset of items excluding 'someone…' phrases, In Tables C1 and C2, we report means and variances for the subset of items that do not include the 'someone…' cases, e.g., all items taking the form "Noun + Verb+ing", where the most important disambiguating linguistic cue appeared in the first word of the phrase. Note that when the 'someone ...' items are removed, accuracy is essentially unchanged, but RT's are slower, interestingly, across both domains – although much more in the linguistic condition, as would be expected. In addition, the correlation between RTs for linguistic and non-linguistic items was slightly stronger and reached conventional levels of significance when calculated only over the 'early-disambiguation' subset of items ($r = 0.36$, $p = 0.04$).

Author Note

Elizabeth Bates, professor of Cognitive Science at the University of California, San Diego, died December 13, 2003, after the revision of this article.

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For more information on running this test on new populations please contact the corresponding author Ayse Pinar Saygin at saygin@crl.ucsd.edu or UCSD Department of Cognitive Science, 9500 Gilman Drive, La Jolla, CA 92093-0515, USA or visit http://crl.ucsd.edu/~saygin/envsounds.html

Footnote

[1] The PsyScope software and documentation is freely available at http://psyscope.psy.cmu.edu/ and can be run on Macintosh computer systems from OS7 to OS9. An adaptation of PsyScope for Macintosh OS X is under development. Note that while the OS 9 version of PsyScope works well for program development in the Classic environment of OS X, response timing may not be as precise in this environment.

Tables

Table 1: Means and standard deviations for Accuracy (in %)

		Younger (N=25)		Older (N=19)	
		Mean	Std. dev.	Mean	Std. dev
Verbal	Unrelated	99.73	0.74	99.65	0.83
	Related	98.49	2.20	98.71	2.00
Nonverbal	Unrelated	99.38	1.20	99.18	1.33
	Related	96.44	3.14	96.96	2.59

Table 2: Means and standard deviations for Reaction Time (in msec)

		Younger (N=25)		Older (N=19)	
		Mean	Std. dev.	Mean	Std. dev
Verbal	Unrelated	946	119	1127	229
	Related	1055	135	1236	251
Nonverbal	Unrelated	717	102	958	275
	Related	890	151	1204	276

Table A1. Properties of the 45 sounds used in the main experiment.

Sound	Identifiability score (Min:0, Max:10)	Reaction time for identification (Mean/Std. dev. in msec)	Duration (msec)
Airplane flying	9	2297 / 926	4185
Alarm clock ringing	7.9	1023 / 352	1024
Baby crying	10	1156 / 540	4326
Basketball	4.2	1180 / 460	704

bouncing			
Bells tolling	10	1594 / 767	2728
Bird chirping	9.5	1252 / 420	1321
Car starting	10	1364 / 919	4001
Cat meowing	9.7	938 / 347	754
Chicken clucking	6.2	1436 / 811	999
Cow mooing	8.7	1300 / 465	1669
Dog barking	10	844 / 279	521
Fly buzzing	9.8	1056 / 382	4319
Grandfather clock chiming	9.4	2038 / 867	3025
Guitar playing	9.9	1761 / 729	3186
Helicopter hovering	9.4	1438 / 512	1869
Horse neighing	9.6	1284 / 508	2553
Lawnmower mowing	7	2028 / 753	2386
Lion growling	9.1	1884 / 909	3286
Piano playing	10	1419 / 665	3016
Rain falling	8.1	2533 / 1039	4458
Rooster crowing	9.8	1009 / 401	1851
Sheep baahing	9.8	1030 / 332	897
Someone bowling	5.8	3213 / 1056	4333
Someone coughing	10	825 / 218	842
Someone diving into water	8.9	1701 / 549	2377
Someone drilling	7.9	2076 / 906	2136
Someone eating an apple	10	1495 / 618	3175
Someone hitting a	4.3	2245 / 1200	1515

baseball			
Someone kissing	10	1694 / 253	1167
Someone playing golf	8.1	1479 / 1140	1341
Someone pouring a drink	9.9	1548 / 711	3695
Someone sawing	10	2026 / 782	2917
Someone sneezing	9.9	852 / 348	1012
Telephone ringing	9.8	796 / 285	3460
Toilet flushing	9.8	1187 / 324	2778
Tractor engine running	8.7	2005 / 780	2705
Train going by	9	2597 / 806	3564
Trumpet playing	9.9	1257 / 513	3007
Vacuum cleaner starting	8.1	1994 / 998	4017
Violin playing	10	1484 / 642	3438
Water boiling	8.6	1307 / 487	3527
Water dripping	9.7	1338 / 554	3088
Whistle blowing	9.5	1084 / 1197	2280
Woman laughing	9.9	911 / 388	2208
Woman singing	10	1490 / 567	4516

Table B1. List of the 45 triplets used in the main experiment

Target picture	Related distracter	Unrelated distracter
airplane	car	sing
alarm clock	grandfather clock	drip
baseball	golf	fly
basketball	bowling	kiss
bells	phone	sneeze
bird	fly	vacuum cleaner
bite	kiss	golf
boil	pour	car
bowling	baseball	pour
car	helicopter	grandfather clock
cat	rooster	boil
chicken	bird	piano
cough	bite	tractor
cow	sheep	violin
cry	sing	basketball
dive	boil	alarm clock
dog	horse	cough

drill	saw	cat
drip	rain	bite
flush	dive	whistle
fly	chicken	bowling
golf	basketball	phone
grandfather clock	bells	cry
guitar	violin	lion
helicopter	train	guitar
horse	cow	drill
kiss	sneeze	baseball
laugh	cry	train
lawnmower	vacuum cleaner	trumpet
lion	cat	dive
phone	whistle	horse
piano	trumpet	rain
pour	drip	airplane
rain	flush	bells
rooster	lion	saw
saw	lawnmower	bird
sheep	dog	helicopter

sing	cough	cow
sneeze	laugh	lawnmower
tractor	airplane	dog
train	tractor	flush
trumpet	guitar	laugh
vacuum cleaner	drill	rooster
violin	piano	chicken
whistle	alarm clock	sheep

Table C1. Means and standard deviations for Accuracy (in %) for the items included in the supplementary analyses.

		Younger (N=25)		Older (N=19)	
		Mean	Std. dev.	Mean	Std. dev
Verbal	Unrelated	99.88	0.59	99.69	0.93
	Related	99.17	1.59	99.69	0.93
Nonverbal	Unrelated	99.29	1.54	99.38	1.57
	Related	96.71	3.21	96.75	3.52

Table C2. Means and standard deviations for Reaction Time (in msec) for the items included in the supplementary analyses.

		Younger (N=25)		Older (N=19)	
		Mean	Std. dev.	Mean	Std. dev
Verbal	Unrelated	867	125	1053	239
	Related	968	151	1163	269
Nonverbal	Unrelated	681	101	930	280
	Related	865	147	1193	271

Figure Captions

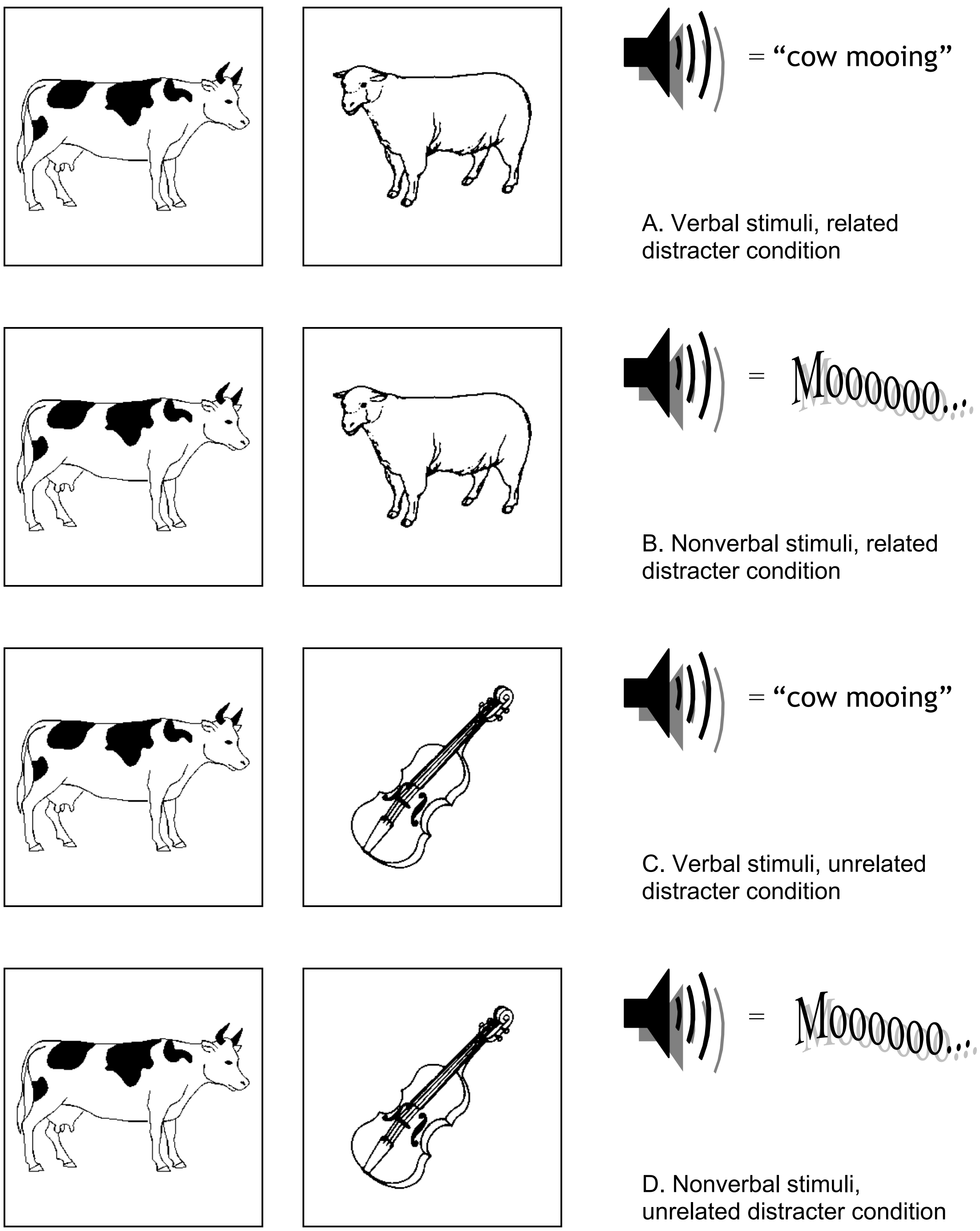
Figure 1. Summary of Experimental Design. Domain (Verbal/Nonverbal) and Distracter Type (Related to target/Unrelated to target) were within-subject factors. The target “cow” appeared four times, twice with verbal sound stimuli (the phrase “cow mooing”), twice with non-verbal stimuli (the sound of a cow mooing), twice with “sheep” as the distracter (related condition), and twice with “violin” as the distracter (unrelated condition). All of these trial types with the target “cow” are depicted in the picture above. 45 pictures and sounds were used as targets and related and unrelated foils, giving rise to 45 triplets such as “cow-sheep-violin” – see Appendix B. A total of 180 trials were administered. Twenty quasi-random orders of the list were rotated among the subjects.

Figure 2. Accuracy results broken down by subject group. Stimulus Domain (Verbal/Nonverbal and Distracter Type (Related/Unrelated) for the two age groups (Older/Younger) are depicted separately. Error bars are one standard error of the mean.

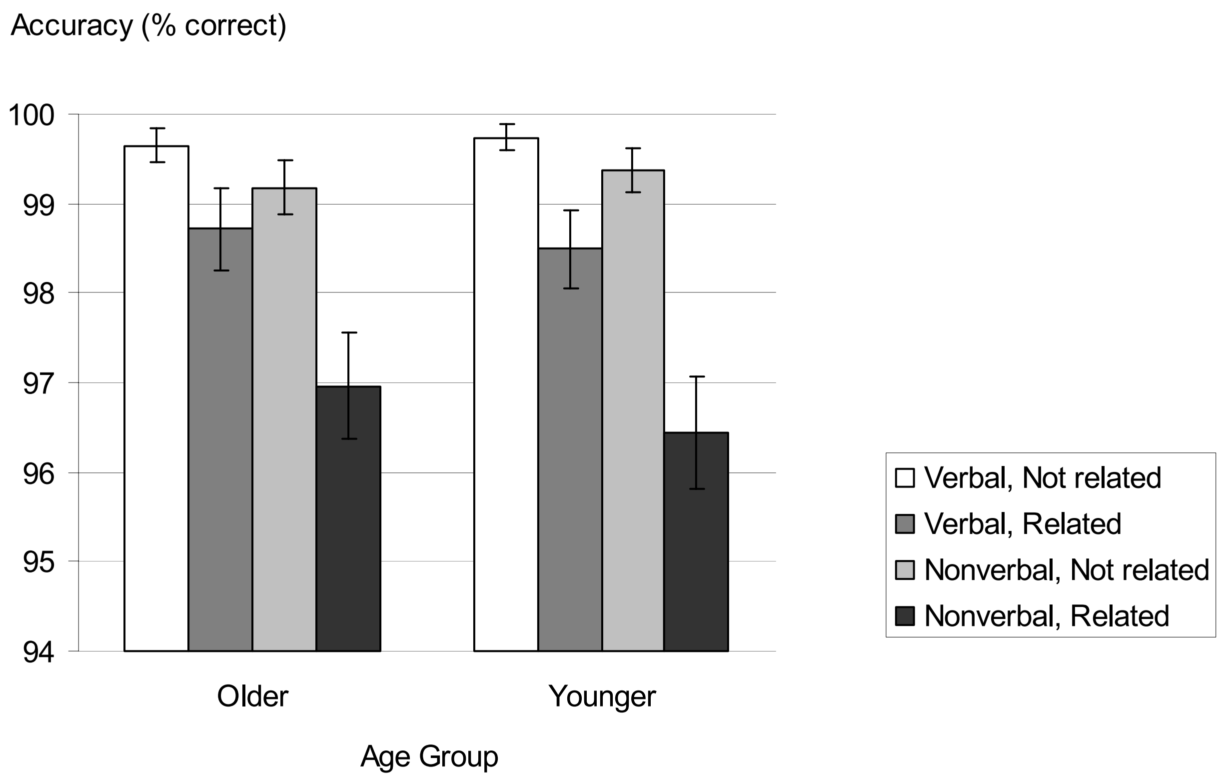
Figure 3. Reaction time results broken down by subject group. Stimulus Domain (Verbal/Nonverbal and Distracter Type (Related/Unrelated) for the two age groups (Older/Younger) are depicted separately. Error bars are one standard error of the mean.

Figures

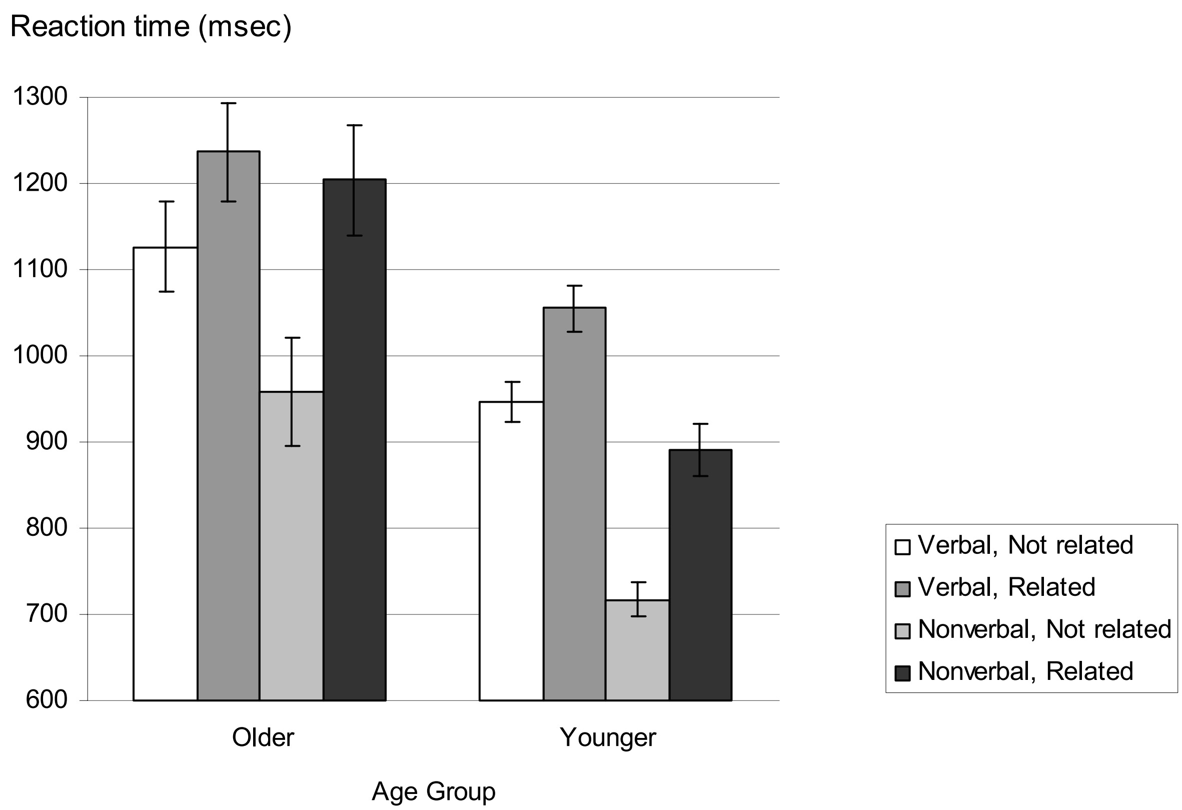
[Figure 1]



[Figure 2]


Accuracy (% correct)
100
99
98
97
96
95
94
Older
Younger
Age Group
Verbal, Not related
Verbal, Related
Nonverbal, Not related
Nonverbal, Related

[Figure 3]


Reaction time (msec)
1300
1200
1100
1000
900
800
700
600
Older
Younger
Age Group
Verbal, Not related
Verbal, Related
Nonverbal, Not related
Nonverbal, Related