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Visual working memory for semantically related objects in healthy adults

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Abstract

Introduction.—Few studies have examined how manipulating the semantic relationship between objects impacts visual working memory accuracy or reaction time.

Aim.—To characterize how the semantic relatedness of visual objects impacts working memory accuracy and reaction time in healthy adults using a newly developed mobile-tablet cognitive task.

Subjects and methods.—A delayed matching to sample paradigm on the tablet task was studied in a sample of 76 community-dwelling adult participants from Spain and Colombia. The tablet task included 80 unique sets of either four or six semantically related or semantically unrelated objects. The accuracy and reaction time of the participants on the task were recorded for analysis.

Results.—When objects were semantically related, reaction time was greater in the six object sets relative to the four object sets. Age was positively associated with reaction time, but not accuracy across all four task conditions. Participants with fewer years of formal education than the sample median (16 years) exhibited worse response accuracy and slower reaction time on both the four and six semantically related conditions relative to participants with 16 or more years of formal education.

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Conclusions.—Findings from this study suggest that when objects are semantically related (versus unrelated) and object load is increased, more processing time is needed to determine whether an object was or was not in the encoded set. The results also suggest that greater educational attainment –which likely relates with greater exposure to more technologies–is related with faster and more accurate responses on some task conditions.

Abstract

Pocos estudios han examinado cómo la manipulación de la relación semántica entre objetos puede influir en el desempeño o el tiempo de reacción en tareas de memoria de trabajo visual.

Caracterizar cómo la relación semántica de los objetos afecta el desempeño o el tiempo de reacción en una tarea de memoria de trabajo en adultos sanos utilizando una tarea cognitiva diseñada para el uso con tableta.

Se usó una tarea de emparejamiento demorado (*delayed matching to sample*) con una muestra de 76 participantes adultos de España y Colombia. La tarea incluyó 80 conjuntos únicos de cuatro o seis objetos relacionados/no relacionados semánticamente. Se registraron las respuestas y el tiempo de reacción de los participantes.

Cuando los objetos estaban semánticamente relacionados, el tiempo de reacción fue mayor en la condición de seis objetos con respecto a la condición de cuatro objetos. La edad se asoció positivamente con el tiempo de reacción, pero no con la precisión de las respuestas. Los participantes con menos años de educación formal tuvieron un peor desempeño y un tiempo de reacción más lento en las condiciones somáticamente relacionadas en relación con los participantes con 16 años o más de educación formal.

Los resultados sugieren que, cuando los objetos están semánticamente relacionados y aumenta su número, se necesita más tiempo de procesamiento para determinar si un objeto está o no en el grupo de objetos codificado. Además, un mayor nivel educativo se relaciona con respuestas más rápidas y un mejor desempeño en ciertas condiciones de la tarea.

Keywords

Cognition; Executive function; Memory; Neuropsychology; Reaction time; Semantics; Short-term

Palabras clave.

Cognición; Corto plazo; Función ejecutiva; Memoria; Neuropsicología; Semántica; Tiempo de reacción

Introduction

Working memory, a cognitive process that has been characterized by the short-term manipulation of stimuli for the purposes of decision making [1], has been classically operationalized into two systems: the phonological loop (which is responsible for auditory working memory) and the visuospatial sketchpad [2]. Working memory processes interact with long-term memory systems to interpret the meaning of auditory or visual stimuli [3]. In the context of visual working memory, previous work has shown that semantic cues enhanced accuracy on a visual matrix working memory task in younger adults [4]. Older adults, however, do not benefit from semantics on the visual matrix task [5], reflective of age-related semantic degradation [6].

Visual working memory has been historically studied through the use of several cognitive tests and experimental paradigms, such as the Delayed Matching to Sample task (DMS) [7,8]. The DMS is a commonly used visual working memory task in which subjects encode several stimuli and, following a brief maintenance period, are asked in a retrieval probe as to whether an object was in the previously encoded set [8]. DMS stimuli are usually images of objects, and an individual taking the test must determine whether the object of a query probe matches one of the previously observed objects. There are many variations of the DMS task that were designed for different purposes. Some variations, for example, present one image on the center of a screen during the encoding period and after a delay the user must select from four images presented simultaneously which image was displayed previously [9].

Daniel et al [7] performed a meta-analysis of forty-two neuroimaging studies and demonstrated that the most common brain regions that are activated during the DMS are located within the frontal and parietal cortices (e.g., the dorsolateral prefrontal and posterior parietal cortices) [7]. Raabe et al [9] similarly found that remembering locations, colors, and orientations of four objects activated different brain regions from the ones activated by just remembering a single object, suggesting greater processing demands at higher object load [9]. The left lateral prefrontal cortex and the anterior temporal cortex are believed to be responsible for the retrieval, maintenance, and selection of semantic information [10-12]. When these brain regions were damaged, visual working memory was also impaired [13-15]. The prefrontal cortex and anterior temporal cortex are also vulnerable to age-related neurodegenerative disorders –such as Alzheimer’s disease and semantic variant primary progressive aphasia– in which semantic memory and visual working memory are compromised early in the clinical syndromes [16-20].

Given the burgeoning presence of mobile phones and tablets, the use of tablet and smartphone-based assessments of cognition is increasingly prevalent [21,22]. Recognizing the demand for new neuropsychological tasks to be available on mobile app platforms, the present research used a mobile-tablet adapted version of the DMS that allowed the semantic relationship of the visual objects to be manipulated between semantically related (SR) or semantically unrelated (SU) across a series of 80 trials. To the best of our knowledge, no DMS adaptation has examined whether manipulating the semantic relationship between objects impacts visual working memory accuracy or reaction time. Decline in semantic memory and visual working memory in the early stages of Alzheimer’s disease and semantic variant primary progressive aphasia (among other disorders) warrants investigating the impact of semantic relationship between objects on visual working accuracy and reaction time. This study examines this question first in healthy adults to lay the foundation for the future research in individuals with age-related neurodegenerative diseases. We hypothesized that increasing task load (from 4 objects to 6 objects) would reduce response accuracy and increase reaction time during the retrieval probe for SR, but not SU trials, and that age would be positively associated with reaction time across all task conditions, but more strongly in the SR conditions relative to the SU conditions. Given previous evidence of age-related semantic degradation [6], we anticipated that task accuracy would decrease and reaction time would increase on all task conditions as a function of increasing age.

Subjects and methods

Participants and IRB approval

Seventy-six community-dwelling adults volunteered to participate in this study in two countries: Spain and Colombia. The inclusion criteria were that participants were between 18 and 60 years old and had a self-report of no known neurological or psychiatric disorders that impact cognitive functioning. This study was approved by the CEICA (Comité de Ética de la Investigación de la Comunidad Autónoma de Aragón – Ethics Committee of Community Investigation of Aragon) in Spain and the local ethics committee at the University of Antioquia in Colombia. Participants signed informed consent forms before taking part in the study.

DMS adaptation task design

We used 220 black-and-white pictures of everyday objects as stimuli for this task. Half of the objects came from 15 semantic categories (animals, kitchen items, bathroom items, vegetables, physical exercise items, junk food, office items, clothing, board games, transportation, furniture, sports, fruits, body parts, and electronic appliances); the categories were created with the presupposition that the objects in the encoding sets would be recognizable (i.e., have semantic meaning) by individuals from different countries. The other half of the objects consisted of combinations of unrelated objects, with some objects not belonging to any specific semantic category. Objects were presented against a gray-scale background.

Our adaptation of the DMS task followed a 2 × 2 design: SR 4 objects, SR 6 objects, SU 4 objects, and SU 6 objects. The SR conditions included only items from the same category (e.g., a pair of pants, a shirt, a hat, and a shoe), and the SU conditions included only semantically unrelated items (e.g., a banana, a car, a toothbrush, and a teddy bear). In total, there were 80 trials (i.e., 20 trials in each condition). Half of the trials in each condition were trials in which the object presented in the retrieval probe was included in the set of objects presented during encoding, whereas in the other half of the trials the probe object was not in the encoding set. Participants were instructed to indicate via button-press whether s/he thought the object was or was not in the observed set as quickly and as accurately as possible. The task conditions were designed to capture reaction time and response accuracy during the retrieval probes. Participants were not informed about the existence of the four conditions. Each trial consisted of four sequentially presented events: brief presentation of 4 or 6 unique pictures of objects (2 seconds per image), a brief delay period (maintenance; 1.5 seconds), a probe period (retrieval), and an inter-trial interval (1.5 seconds). Figure 1 presents an example of this DMS task adaptation with 4 SR (category: animals) and 4 SU images; the 6-image trials follow an identical format to the 4-image trials but use six images. Participants viewed task instructions in Spanish before completing the task. During the inter-trial interval, participants viewed a mask composed of a gray box of the same dimensions as the objects with a black fixation cross in the center. Trials were presented in a randomized and counterbalanced fashion.

Development and deployment of the DMS adaptation

This mobile application adaptation of DMS was developed in collaboration between investigators from Spain and the United States in the fields of computer science and clinical neuropsychology. Investigators used the Framework for Developing m-Health Apps [23] within the Unity 3D environment using the C# programming language to develop the tablet-based DMS adaptation. Reaction time and response accuracy were recorded via the mobile application and stored on the mobile device before being transferred to a computer at Massachusetts General Hospital for storage and data analysis. The app was designed for being rendered at its highest quality in full high definition resolution (i.e., 1920 × 1080), although it can also be observed in any other resolution.

Our DMS adaptation was developed by a user-centered process. The DMS adaptation was initially conceptualized by a neuropsychologist (author Y.T.Q.). A specialist in software development (author I.G.M) implemented an initial prototype with assistance from two other co-authors (J.T.F.F. and G.P.N.). The co-authors, as well as other members of the research lab, tested the initial protocol of the app and suggested improvements for usability. Author I.G.M. then revised the application to implement the suggested improvements with the assistance of author J.T.F.F. This process was repeated until all co-authors were satisfied with the application of the DMS adaptation. Seventeen additional individuals (not part of the study reported here) then used the app in a pilot and suggested additional improvements. We examined pilot data and the comments from these users about the application and implemented additional minor design changes (e.g., replacing an image that was repeated in two trials). The pilot also was a feasibility study to determine if the level of task difficulty was adequate for adult participants. All initial pilot participants self-reported as healthy and had no history of neurological disorders. Pilot task accuracy was substantially above chance (50%) for all participants.

The DMS app was developed in two different languages, English and Spanish, with the goal of using it in several Spanish-speaking countries (e.g., the work presented here from Colombia and Spain), as well as in the United States and other English-speaking nations. Authors I.G.M. (native of Spain), J.T.F.F. (native of the United States), and Y.T.Q. (native of Colombia) are all bilingual English-Spanish speakers and participated in the design and translation of the task instructions in both languages. This DMS adaptation begins by presenting simple instructions on a single screen that tell users that the app will show series of either four or six images. The app then informs the user that after seeing a series of objects they will briefly see a fixation cross and then they will be asked to indicate via finger-press on the app's buttons whether they have observed a certain object 'yes' or 'no'). Participants were also told that after the probe question another fixation cross will appear to indicate that a new encoding trial will begin. Users were told in the instructions to answer during the retrieval probe as quickly and accurately as possible.

The app showed images in black-white always using the same area of the screen with the same gray-screen background color in all the images. Objects were shown using a square ratio that expands until the square occupies 81% of the height of the screen or 40% of the width screen. The app used a landscape layout, and all the images were adapted to have a similar size appearance within this square. Figure 2 shows a screenshot of the app asking a sample retrieval probe question. The right-upper corner shows the number of trials that the participant has completed so the participant can know how many trials still need to be completed.

After the initial pre-pilot with the seventeen participants (who are not part of this study), authors A.B. and G.P.N. collected data using the task from 76 community dwelling healthy adults in Spain and Colombia. Participants volunteered to partake in this short study of our DMS adaptation, with all procedures (consenting through task completion) taking less than 30 minutes.

Statistical analyses

We conducted paired *t*-tests in SPSS v. 24 to determine whether there were differences in reaction time and response accuracy across the four conditions of the task. A median split of years of formal education (median: 16 years) was used in an independent sample *t*-test to analyze if response accuracy or reaction time differed as a function of educational attainment. To characterize how the age of participants was independently related to reaction time and response accuracy we conducted Pearson's correlations; partial correlations were also used to determine the effect of age on reaction time and response accuracy while controlling for years of formal education.

Results

Demographics

76 healthy adults between the ages 18 and 60 were recruited in Spain and Colombia to test this application. 38 of the participants were from Colombia, and 38 of the participants were female. Across both countries, participants were an average of 41.34 ± 12.85 years old and had a mean of 15.09 ± 4.83 years of education. Participants from Spain and Colombia did not differ on age (Colombia: 38.87 ± 3.59 years; Spain: 43.82 ± 11.72 years; $t_{(74)} = 1.70$; $p = 0.09$) or the proportion of males-to-females ($\chi^2 = 1.89$; $p = 0.16$), but Spaniard participants on average had more years of formal education (17.04 ± 4.40 years) than Colombian participants (12.14 ± 4.74); $t_{(74)} = 4.43$; $p < 0.01$). Spaniard participants also had faster reaction times across all four task conditions relative to Colombians ($t_{(74)}$ ranging from −2.32 to −3.72; *p* ranging between 0.02 to < 0.01), but the groups did not differ on response accuracy across task conditions.

Behavioral task performance

Across all participants, mean response accuracy was high (92-96% on average) for both SR and SU conditions on all task loads; all participants achieved accuracy at or above chance (50%) across all task conditions. When examining the effect of education on accuracy and reaction time on this task, relative to individuals with 15 years or less of formal education participants with greater than or equal to 16 years of formal education performed significantly better on the 4 SR (97.25 ± 4.29% versus 93.06 ± 10.23%; $t_{(74)} = 2.38$; $p =$

0.01) and 6 SR conditions (94.75 ± 5.31% versus 93.61 ± 10.99%; $t_{(74)} = 0.561$; $p = 0.025$). The reaction time of participants, as a whole, ranged between 920 and 4200 ms across all conditions. The mean reaction time on the task conditions were as follows: 4 SR (1735 ± 570 ms), 6 SR (1829 ± 598 ms), 4 SU (1785 ± 634 ms), 6 SU (1812 ± 658 ms). Participants did not differ on reaction time on any task condition as a function of educational attainment ($p > 0.05$ for all).

Regardless of the semantic relationship between objects, across all participants response accuracy was lower in 6 object conditions (93.7 ± 8.3%) relative to 4 object conditions (95.1 ± 7.43%); $t_{(75)} = 2.38$; $p = 0.02$. Average response accuracy on 4 and 6 object trials, irrespective of semantic relation, did not differ between participants with fewer and greater years of formal education. Average reaction time was similarly greater in the 6 object conditions (1820 ± 620 ms) relative to 4 object conditions (1760 ± 711 ms), irrespective of semantic relationship; $t_{(75)} = -2.94$; $p < 0.01$. Regardless of the semantic relationship between objects, participants with fewer years of formal education had slower reaction times than participants with more years of formal education across 4 (1924 ± 691 ms versus 1613 ± 437 ms; $t_{(74)} = -2.37$; $p = 0.02$) and 6 object conditions (1975 ± 732 ms versus 1681 ± 466 ms; $t_{(74)} = -2.11$; $p = 0.03$).

Across all participants, when examining increasing visual working memory object load in the context of the semantic manipulation, however, average reaction time was significantly greater in 6 object (1829 ± 598 ms) relative to the 4 object sets (1735 ± 570 ms) when the object sets were semantically related ($t_{(75)} = -3.72$; $p < 0.001$), but not when the objects were semantically unrelated; $t_{(75)} = -1.02$; $p = 0.31$.

Conversely, average response accuracy was only significantly better in 4 object (94.9 ± 7.7%) relative to 6 objects sets (93.2 ± 9.3%) when the object sets were semantically unrelated; $t_{(75)} = 2.22$; $p = 0.03$. This was not the case when objects were semantically related; $t_{(75)} = 1.63$; $p = 0.11$.

Associations between participant age with response accuracy and reaction time

To determine whether response accuracy or reaction time on this task were sensitive to age-related changes in visual working memory, we evaluated the correlations between age with response accuracy and reaction time for the different task conditions. Age was not independently associated with response accuracy across groups but was significantly associated with reaction time on all 4 of the task conditions (4 SR: $r = 0.31$, $p < 0.01$; 4 SU: $r = 0.26$, $p = 0.03$; 6 SR: $r = 0.32$, $p < 0.01$; 6 SU: $r = 0.24$, $p = 0.04$). Figure 3 shows the associations between age and reaction time on all task conditions. When controlling for educational attainment, the associations between age and reaction time were significant in the 4 SR ($r = 0.23$, $p = 0.05$) and 6 SR conditions ($r = 0.25$, $p = 0.03$) only.

Discussion

Our mobile-tablet adaptation of the DMS allowed us to explore the impact of semantic relationship (or lack thereof) on reaction time and response accuracy in healthy Spanish-speaking adults from Spain and Colombia. Findings from this study demonstrate that although increasing load from 4 to 6 objects resulted in an average increase in reaction time during the retrieval probe, this increase in reaction time was preferentially seen among object sets that were semantically related. Reaction time was significantly greater in the 6 SR trials relative to the 4 SR trials, suggesting that this modification of the DMS may be most sensitive to visual working memory-related processes that require greater processing time, such as an increased task load (i.e., 6 objects vs. 4 objects). The observed correlations between age and reaction time on all task conditions aligns with work from previous other iterations of the DMS and other visual working memory tasks [24,25]. We also found that participants with fewer than 16 years of formal education (the median split for our sample) exhibited slightly worse response accuracy on both the 4 and 6 SR conditions relative to participants with 16 or more years of formal education, though there were no significant differences on reaction time on any task condition as a function of educational attainment. Irrespective of semantic relationship, participants with fewer than 16 years of formal education exhibited slower reaction time across the averages of the 4 and 6 object conditions; there were no significant differences, however, in the average accuracy of 4 and 6 object trials as a function of educational attainment. Taken together the results from this study suggest that reaction time on this visual working memory is sensitive to advancing age (more so than task accuracy), and when objects are semantically related more processing time is needed during the retrieval probe than when objects in are semantically unrelated.

When objects are semantically related, we propose that more reaction time is needed because the items in the same semantic category (e.g., fruit) must be encoded as more specific item-level representations in visual working memory (e.g., grape, apple, orange), whereas unrelated items (e.g., a hat, a dog) can be encoded and retrieved successfully at a non-specific category representation (e.g., clothing, an animal). The prospective process of having to first understand the semantic category of objects and then encode semantically related objects as more distinct items may be particularly challenging, especially as individuals age and semantic degradation occurs [6,26]. Given that this task involves the encoding, maintenance and retrieval of semantically related objects in visual working memory, the lateral prefrontal cortex and the anterior temporal cortex may be involved in optimizing performance on this task [10-12]. These frontal and temporal brain regions have been shown to be negatively impacted by advancing age [27,28]. Future work with this DMS adaptation will need to use neuroimaging techniques to investigate whether performance and reaction time on this task correlates with functional activation in these neuroanatomical regions. Additionally, studying how accuracy and reaction time in healthy controls differs from individuals with neurological disorders that preferentially impact the lateral prefrontal cortex and the anterior temporal cortex –such as Alzheimer's disease and semantic variant primary progressive aphasia– will also be experimentally and clinically informative [16-20].

A limitation of this study is that we cannot ascertain the degree to which this assessment converges with extant working memory assessments, as participants did not complete other working memory tasks. Similarly, participants did not undergo functional neuroimaging during this task, so we cannot know whether activity in regions of the brain responsible for visual working memory and semantics was changed during different task procedures (e.g., encoding or retrieval probe) versus rest. We plan to further study this DMS mobile modification in cognitively normal individuals and compare results against previously validated working memory tasks (e.g., the Wechsler Adult Intelligence Scale-IV Digit Span [29]). Other versions of the DMS have demonstrated convergence with other working memory tests and activation in working memory-related brain regions [7], so we anticipate that our DMS mobile-assessment will yield similar results. It is possible that this new DMS mobile modification app will converge with other tests of executive function outside of working memory as well, as many executive functions share common neuroanatomical and clinical correlates [30,31].

Another limitation of our work is that the data in this study are from Colombia and Spain only; data from other countries (e.g., the United States of America) is planned to be gathered in future research using this DMS adaptation. Furthermore, despite the app in this study being developed in a cross-cultural framework, some aspects of task performance on our mobile app –like many existing cognitive tests– appear to be impacted by educational attainment. The impact of education on response accuracy on semantically related object tests and average reaction times at 4 versus 6 object loads (irrespective of semantic relationship) suggests that years of formal schooling may inadvertently influence performance on this task. Years of formal education may play a role on task performance through one particularly clear mechanism –familiarity with technology, such as mobile tablets. As people go through more years of formal schooling, individuals are generally more exposed to the mobile app technology similar to what was used in this study. Similar to other neuropsychological tests, future work with this mobile application will need to focus on developing norms for accuracy and reaction time on the task conditions as a function of both age and educational attainment.

In conclusion, we showed that the semantic relationship between objects, paired with increasing object load (4 vs. 6 objects) is linked with an increased demand for reaction time during retrieval on a visual working memory task. Reaction time on all task conditions was positively associated with age, pointing to this task's sensitivity to age-related changes in visual working memory and semantic processing that are seen in healthy aging and a variety of neurological disorders. This preliminary work sets the stage for future research on visual working memory for semantically related and unrelated objects, which is important experimentally and also clinically as the field searches for new, sensitive ways to assess for the earliest observable cognitive changes in age-related neurological disorders.

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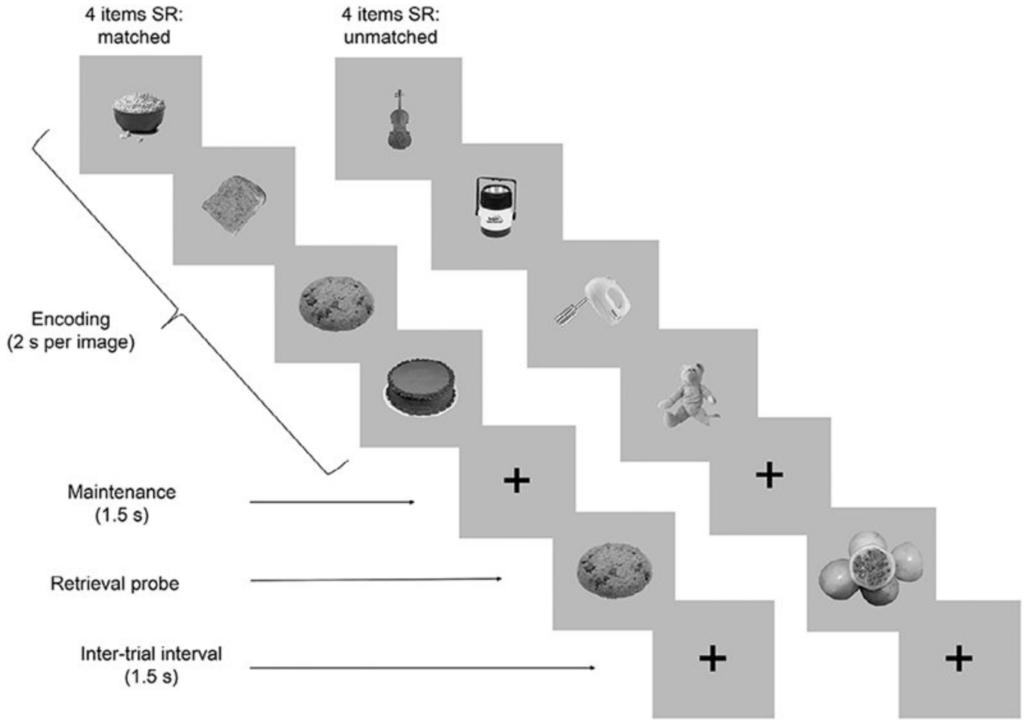

Figure 1.
Design of delayed matching to sample (DMS) adaptation. Two examples of our DMS task adaptation are presented to demonstrate how semantically related or semantically unrelated objects are presented during encoding and then asked about during the retrieval probe; the task includes trials that use 4 objects (like those shown), as well as trials using 6 objects.

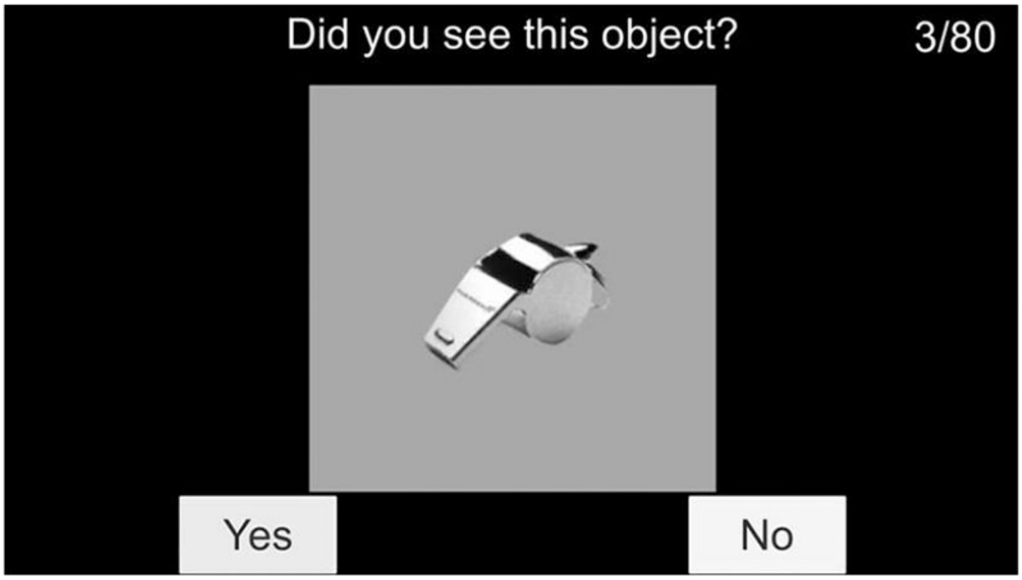

Figure 2.

Participant view of the mobile tablet adaptation of probe question of the delayed matching to sample (DMS) task. A screenshot of the retrieval probe question is presented to demonstrate the relative simplicity of this adapted DMS task design. After the encoding of either 4 or 6 objects and a maintenance period of 1.5 seconds, users were presented with something similar to the above screen where an object is presented with the question 'Did you see this object?' and two touch boxes ('yes' and 'no'). The version employed in the current study was our Spanish translation, which asked this question and had the touch boxes in Spanish. The ratio at the top right of the screen is the number of completed trials out of the 80 total trials.

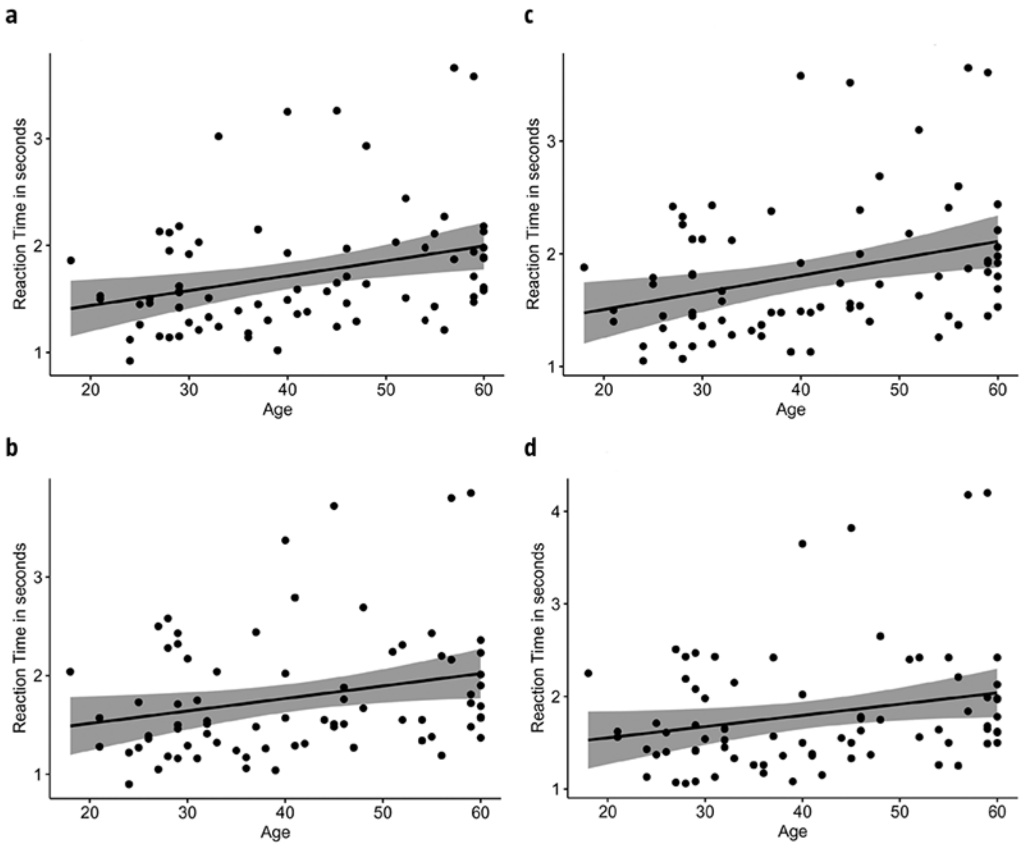

Figure 3.

Associations between reaction time with age on all task conditions. The correlations between age and reaction time on: a) 4 SR ($r = 0.31$, $p < 0.01$); b) 4 SU ($r = 0.26$, $p = 0.03$); c) 6 SR ($r = 0.32$, $p < 0.01$); d) 6 SU ($r = 0.24$, $p = 0.04$), are shown. SR: semantically related; SU; semantically unrelated.