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The Influence of Stimulus Complexity on the Effectiveness of Visual Associative Learning

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Abstract—Visually guided equivalence learning is a special type of associative learning, which can be evaluated using the Rutgers Acquired Equivalence Test (RAET) among other tests. RAET applies complex stimuli (faces and colored fish) between which the test subjects build associations. The complexity of these stimuli offers the test subject several clues that might ease association learning. To reduce the number of such clues, we developed an equivalence learning test (Polygon), which is structured as RAET but uses simple grayscale geometric shapes instead of faces and colored fish. In this study, we compared the psychophysical performances of the same healthy volunteers in both RAET and Polygon test. Equivalence learning, which is a basal ganglia-associated form of learning, appears to be strongly influenced by the complexity of the visual stimuli. The simple geometric shapes were associated with poor performance as compared to faces and fish. However, the difference in stimulus complexity did not affect performance in the retrieval and transfer parts of the test phase, which are assumed to be mediated by the hippocampi.

Key words: visual, equivalence learning, basal ganglia, hippocampi, psychophysics, healthy human.

INTRODUCTION

Associative learning is an evolutionarily ancient basic cognitive function in which discrete and even different ideas and perceptions are linked together and thus can elicit similar behavioral responses. Typical forms of this learning include classical conditioning (Ito et al., 2008), probabilistic learning (Shohamy et al., 2009), weather prediction (Gluck et al., 2002), latent inhibition (Weiss and Brown, 1974), and sensory preconditioning (Rescorla, 1980). Visually guided equivalence learning is a special type of associative learning, which can be evaluated using the Rutgers Acquired Equivalence Test (RAET) among other tests. In this simple test with well-established neural background (Shohamy and Wagner, 2008), the subject learns that two or more stimuli are equivalent in terms of being mapped onto the same outcomes or responses (Myers et al., 2003). Basically, the paradigm consists of two primary components, acquisition and test phases. In the acquisition phase, the subjects learn to associate pairs of visual stimuli (cartoon faces and colored fish) on the basis of computer feedback on the correctness of the associations (trial-and-error learning). The acquisition phase consists of parts characterized by low working memory load (shaping and the equivalence training) and high working memory load (introduction of new consequents, see Table 1, Puszta et al., 2020).

In the test phase, where no feedback is given on the correctness of the responses, the previously learned (retrieval part of the test phase) or hitherto not shown, but predictable associations are tested (generalization or transfer parts of the test phase). The original paper by Myers et al. (2003) reported that performance in the acquisition phase was affected in Parkinson's disease, and the generalization part of the test phase was affected in hippocampal atrophy. Subsequent psychophysical and neuroimaging studies (Cohen et al., 1999; Gogtay et al., 2006; Persson et al., 2014; Larsen and Luna, 2015; Porter et al., 2015) demonstrated that the equivalence learning phase is linked primarily to the basal ganglia-frontal cortex loops and the test phase is linked to the hippocampi. These observations allow the conclusion that the striatum and hippocampi are structures of key importance for association and generalization, respectively, which is in line with our knowledge on the memory functions of these structures (Cohen et al., 1999; Packard and Knowlton, 2002). Not surprisingly, in several other neurological and psychiatric disorders characterized by the dysfunction of the basal ganglia and hippocampi, per-

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Table 1. A summary of the visual associative learning paradigms. A,B: antecedents (faces in RAET and circles in Polygon), X,Y: consequents (fish in RAET and simple geometric forms in Polygon)

ACQUISITION			TEST	
Shaping	Equivalence training	New consequents	Retrieval	Generalization
A1 → X1	A1 → X1	A1 → X1	A1 → X1	
	A2 → X1	A2 → X1	A2 → X1	
		A1 → X2	A1 → X2	
				A2 → X2
B1 → Y1	B1 → Y1	B1 → Y1	B1 → Y1	
	B2 → Y1	B2 → Y1	B2 → Y1	
		B1 → Y2	B1 → Y2	
				B2 → Y2

formance deficit was found. Such disorders include Parkinson's disease (Myers et al., 2003), adult migraine (Oze et al., 2017), the Tourette syndrome (Eördegh et al., 2020), hippocampal atrophy (Moustafa et al., 2010), and schizophrenia (Keri et al., 2005). In contrast, no deficit was found in children with obsessive–compulsive disorder (Pertich et al., 2020) and migraine (Giricz et al., 2021). However, it is possible that in the latter two cases, it is only that RAET is not sensitive enough to detect the difference. We argue that in RAET, which applies potentially meaningful and colored stimuli, the stimuli might also elicit emotional responses, which could serve as clues to help association learning. To address this issue, we developed a visual associative learning test (Polygon), which is based on the same principles as RAET, but it uses simple grayscale geometric shapes instead of faces and fish. In the present study, we examined the performance of healthy volunteers in both tests.

Previous studies demonstrated that stimulus complexity could affect auditory-guided associative learning, and more complex stimuli could elicit better responses with more prominent cortical activation (Gucluturk et al., 2018; Staib and Bach, 2018; Maor et al., 2020). Based on these findings, we explored whether the complexity of visual stimuli could influence performance in visually guided equivalence learning. Our hypothesis was that our subjects' performance would be inferior in Polygon as compared to RAET because the stimuli in Polygon contain fewer clues. Special attention was focused on whether these possible differences are similar or different in the acquisition and test phases of the learning paradigms.

EXPERIMENTAL PROCEDURES

Subjects

Fifty-five healthy adults participated in this study (26 women and 29 men, mean age: 35.11 ± 13.925 years, range: 18–65 years). The participants were recruited on a voluntary basis, received no compensation for their participation, and they were free to quit at any time without any consequence (one subject did so). The volunteers were informed about the aims and procedures of the study, and their medical history was taken with emphasis on any neurological or psychiatric disorders. Volunteers with such disorders in their history were not eligible for the study. The volunteers were also tested with the Ishihara plates to exclude color blindness. Those who decided to participate, signed an informed consent form. The study protocol followed the tenets of the Declaration of Helsinki in all respects, and it was approved by the Regional Research Ethics Committee for Medical Research at the University of Szeged, Hungary (27/2020-SZTE).

Visually guided associative learning paradigms

Tests were run on two laptops (Lenovo Think Book 15-IIL). The subjects were tested in a quiet room sitting at a standard distance (57 cm) from the laptop screen (stimuli were equal in size, of a maximum diameter of 5 cm, which corresponds to a 5° angle of view). The subjects were tested separately, one subject at a time. No time limit was set, and no forced quick responses were expected. The keys X and M were labeled as "left" and "right" on the laptop's keyboard. The subjects used these keys to indicate their choices in both test paradigms.

In this study, we applied two visually guided associative learning paradigms: RAET and Polygon.

RAET was carried out according to Myers and coworkers (Myers et al., 2003). The testing software (originally written for iOS) was used and rewritten in Assembly (for Windows) with the written permission of Myers and colleagues at Rutgers University, NJ (Oze et al., 2017).

The antecedent stimuli were cartoon faces of a woman (A1), a girl (A2), a man (B1) and a boy (B2) with black or brown hair. The consequent stimuli were yellow (X1), red (X2), green (Y1) and blue (Y2) fish. The shape of the fishes were the same, they differed only in their color.

During a trial, the participant was presented with an antecedent (a face) and two consequents (a pair of fish of different color) and asked to choose one of the latter by pressing either the "left" or "right" button on the keyboard (Fig. 1).

The trials were organized into two main phases: acquisition and test. The test phase was further broken down to retrieval and generalization (see below). In the acquisition phase, the choice was followed by feedback on the correctness of the choice (trial and error learning) and there was no feedback in the test phase.

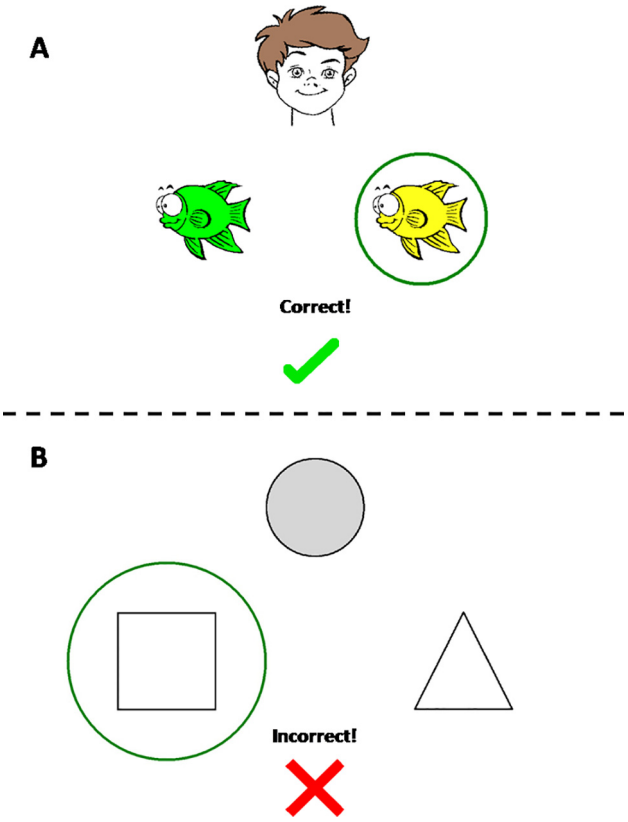

Fig. 1. A trial in the acquisition phase of RAET **(A)** and Polygon **(B).** Above is the antecedent and below are the possible consequents. By pressing the ‘‘left” or ‘‘right” button, the subject guesses which consequent belongs to the given antecedent. Immediate visual feedback is given. If the guess is right, a green checkmark appears. If the guess is wrong, it is indicated by a red X mark. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

During the acquisition phase, the participants learned a series of antecedent-consequent pairs via trial and error. When face A1 or face A2 were shown, the correct choice was fish X1 over fish Y1; however, when face B1 or face B2 appeared on the screen, the correct answer was fish Y1, instead of fish X1 (Table 1, Fig. 2). Visual feedback on the correctness of the subject’s choice was always given immediately in the form of a checkmark (in green) or an X mark (in red) displayed on the screen under the actual antecedent-consequent pair. This way, besides the face-fish associations, the participants also learned that the face A1 is equivalent to face A2 in terms of their relation to the consequents (fish). New associations were introduced gradually, and they were presented mixed with trials of previously learned associations. The subjects had to achieve a certain number of consecutive correct answers after the presentation of each new association to be allowed to proceed. This number was 2 when the first association was presented, and it was increased by 2 upon the presentation of each association that followed (up to a maximum of 12). Thus, the length of the acquisition phase varied among the participants, depending upon how efficiently they learned. Altogether six of the eight possible associations were presented in the acquisition phase (each of the 4 faces associated with 2 fish). The rule of association, i.e. which stimulus feature (age, sex or hair color) is used to link the antecedent pairs, was generated randomly by the software for each subject, and it remained the same until the end of the test. The subjects were not aware of the rule of association at the beginning of testing, they had to figure it out for themselves through trial and error.

If the acquisition was successful, subjects continued with the test phase. In the test phase, the task remained the same, but visual feedback was no longer provided. In this phase, the subjects had to recall the previously learned six associations (retrieval part) and they had to identify the two new, hitherto not presented but predictable associations (generalization part). In contrast to the acquisition phase, the test phase always involved 48 trials (12 new and 36 previously learned associations). Subjects were not informed that new associations would have to be formed, only that their task remained the same, but without feedback.

Polygon is a modified version of RAET with simple geometric shapes as stimuli (Table 1, Fig. 1B, and Fig. 3).

We applied simple geometric shapes to reduce the chance that the stimuli evoke emotional responses or cognitive associations that could serve as clues for associative learning. Instead of faces, we applied circles with different contrasts (white, light gray, dark gray, and black) as antecedents. Instead of fish with different colors, we applied simple geometric shapes (triangle, square, rhombus, and concave deltoid) with no coloring as consequents (Fig. 3).

The subjects completed both equivalence learning tests one after the other, and in random order to avoid carryover.

Data analysis

We analyzed the number of trials required for completing the acquisition phase (NAT), response accuracy for the various stages of the paradigms (error ratios), and reaction times (RTs, the time between the appearance of the stimuli and the decision of the participant as indicated by pressing one of the designated keys on the keyboard). Error ratios were calculated in Microsoft Excel (2016) with a custom-made script by dividing the number of incorrect answers by the total number of trials in the acquisition phase (acquisition learning error ratio = ALER), the retrieval (retrieval error ratio = RER), and generalization parts (generalization error ratio = GER) of the test phase. RT was measured with millisecond accuracy. RT values of > 3 SD were excluded from further analysis.

Statistical analysis was conducted in Statistica 13.4.0.14 (TIBCO Software Inc., USA). Data distributions were evaluated using the Shapiro–Wilk normality test. As the data sets were non-normally distributed, the Wilcoxon matched-pairs test was used for the comparisons between the paradigms. We also performed effect size and power calculations for the significant differences in G*Power 3.1.9.2 (Düsseldorf, Germany).

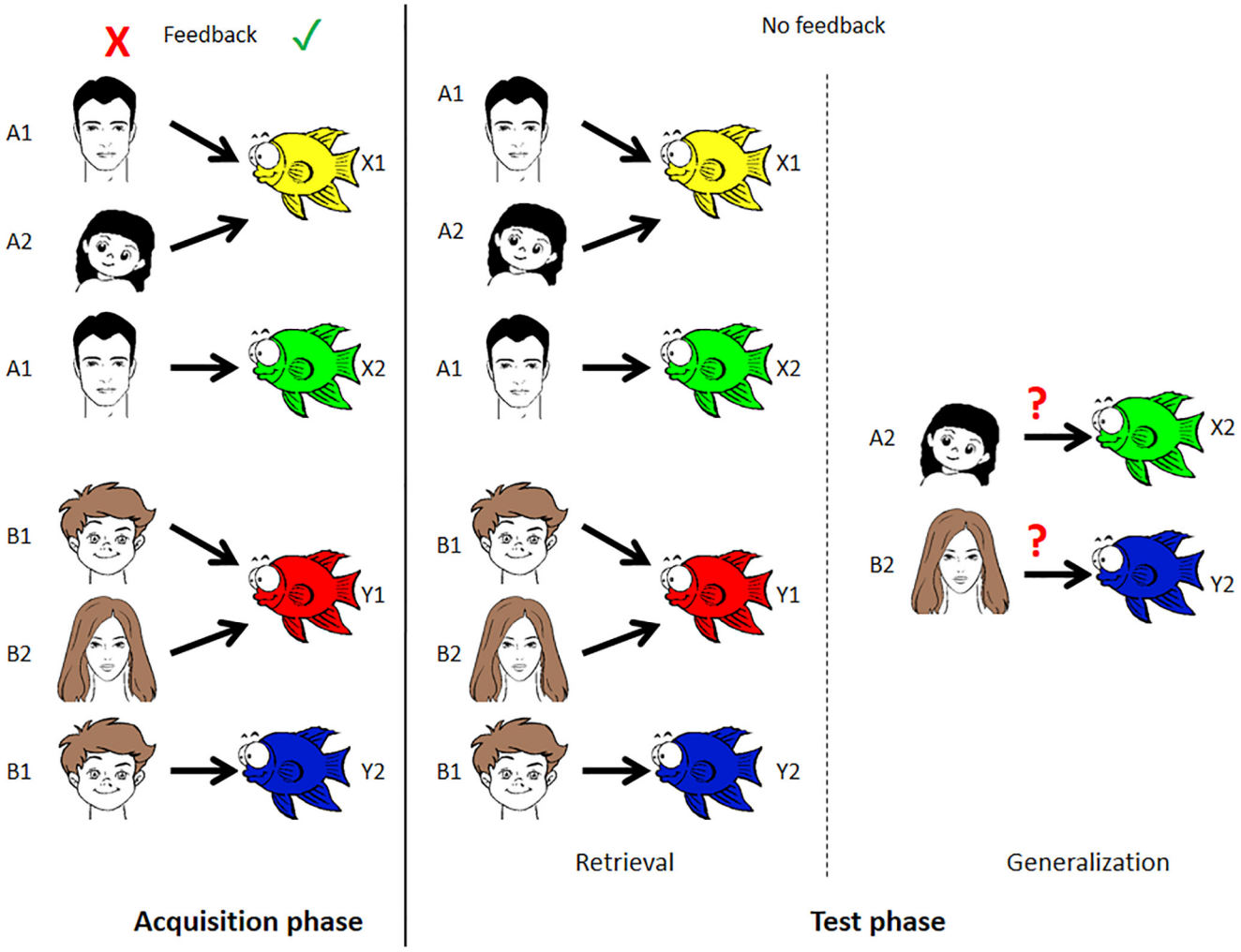

Fig. 2. Overview structure of the original Rutgers Acquired Equivalence Test. The antecedent–consequent pairs of the test. The antecedents were cartoon faces of a man (A1) a girl (A2), a boy (B1) and woman (1). The consequents (responses) were drawings of fish of yellow (X1), green (X2), red (Y1) and blue (Y2) colors. In this example, the basis of equivalence is hair color.

Data availability

The datasets are available from the corresponding author on reasonable request.

RESULTS

Fifty-four of the 55 subjects completed both paradigms. One subject could not complete Polygon. The data of this subject were not included in the analyses.

As a preliminary analysis, we assessed if the order of the administration of the paradigms (RAET-Polygon $n = 26$ or Polygon-RAET $n = 28$) had any effect on the subjects' performance. The subjects were divided into two groups based on the order in which they completed the paradigms, and we compared their performance according to the already described parameters (NAT, ALER RER, GER, RT, see before in the Experimental Procedures) for both paradigms. For this analysis, the Mann–Whitney *U* test was used. The analysis found no significant difference in any of the parameters in either paradigm (Mann–Whitney *U* test, $p > 0.05$). The temporal evolution of the psychophysical performances (NAT, ALER RER, GER, RT) were not affected to a considerable degree by the order of administration either (Supplementary Figs. 1–4). It was also tested for both paradigms if completing a paradigm as first or second in the testing sequence influenced the subjects' performance. No significant difference was detected (Mann–Whitney *U* test, $p > 0.05$), that is, whether the same paradigm was administered as first or second had no or negligible effect.

Acquisition phase

The median of the number of trials required for completing the acquisition phase (NAT) in RAET was 54.0 (range: 43.0–136.0), but it was 68.5 (range: 42.0–213.0) in Polygon. In Polygon, significantly more trials were required for the learning of the associations than in RAET (Wilcoxon matched-pairs test $Z = 3.731$, $p = 0.0002$, effect size 0.6268, power 0.9538, Fig. 4). In RAET, the median of acquisition learning error ratio

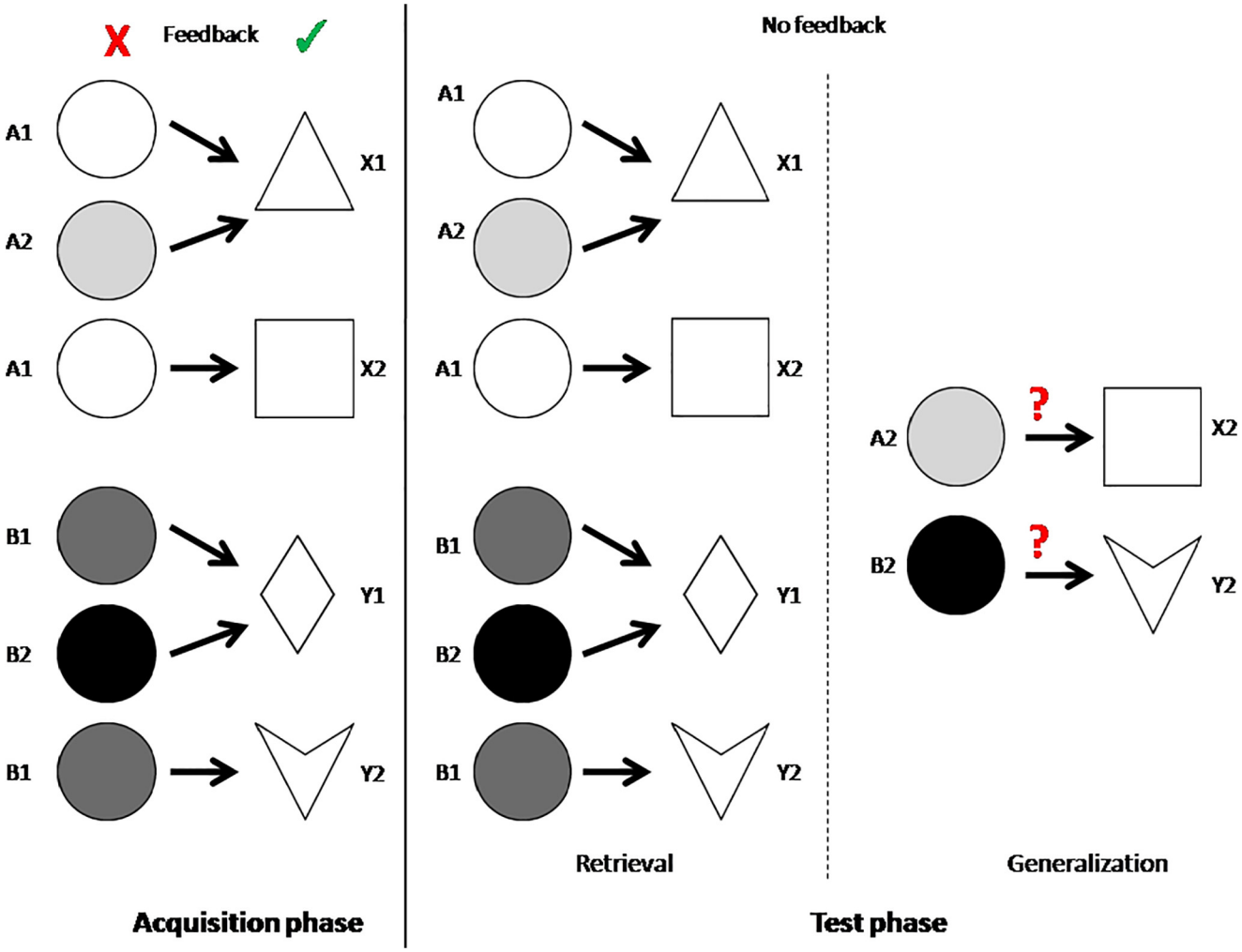

Fig. 3. Overview structure of the new visual acquired equivalence paradigm (Polygon). The antecedent–consequent pairs of the test. The antecedents were circles filled with different shades of the grayscale: white (A1), light gray (A2), dark gray (B1) and black (1). The consequents (responses) were different polygons: a triangle (X1), square (X2), rhombus (Y1) and concave deltoid (Y2). In this example, the basis of equivalence is low contrast difference.

(ALER) was 0.052 (range: 0.0–0.240), and in the Polygon test, it was 0.096 (range: 0.0–0.340). This difference was also highly significant (Wilcoxon matched-pairs test $Z = 3.939$, $p = 0.00008$, effect size 0.6984, power 0.9520, Fig. 4).

The comparison of the low and high working memory load parts of the acquisition phase (see Table 1) revealed that the performances in both the low- and high-load parts were significantly superior in RAET. The median value of NAT in the equivalence training part (low working memory load) was 27.0 trials (range: 22.0–76.0) in RAET, and 33.0 trials (range: 22.0–72.0) in Polygon (Wilcoxon matched-pairs test: $p = 0.0019$). The median value of NAT in the high working memory load part (introduction of new consequents) was 26.5 (range: 22.0–91.0) in RAET and 32.5 (range: 22.0–157.0) in Polygon (Wilcoxon matched-pairs test: $p = 0.0091$).

ALERs were also lower in both the low working memory load and the high working memory load parts of the acquisition phase in RAET. The median value of the ALER the equivalence training part (low working memory load) was 0.07275 (range: 0.0–0.2933) in RAET and 0.12702 (range: 0.0–0.4688) Polygon (Wilcoxon matched-pairs test: $p = 0.0013$). The median value of the ALER in the high working memory load part (introduction of new consequents) was 0.04348 (range: 0.0–0.1778) in RAET and 0.06155 (range: 0.0–0.3013) in Polygon (Wilcoxon matched-pairs test: $p = 0.0648$).

Reaction times (RTs) were also significantly longer in Polygon (Wilcoxon matched-pairs test $Z = 2.983$, $p = 0.003$, effect size 0.4862, power 0.9521). The median RT in RAET was 1606.22 ms (range: 1004.74–3 052.88 ms), and 1802.06 ms in Polygon (range: 888.4 9–4618.79 ms).

Test phase

In contrast to the acquisition phase, no significant performance differences were found between the paradigms either in the retrieval (Wilcoxon matched-pairs test $Z = 0.739$, $p = 0.460$) or the generalization parts of the test phase (Wilcoxon matched-pairs test

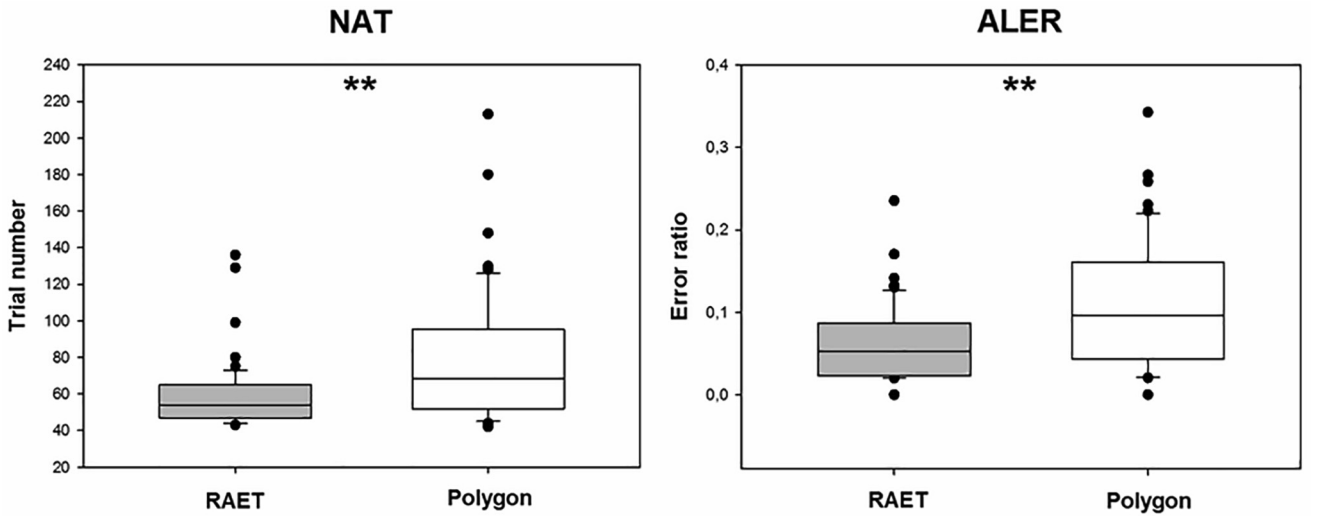

Fig. 4. Comparison of performances in the acquisition phase of the two associative learning paradigms. NAT: number of acquisition trials. ALER: acquisition learning error ratio. The lower margin of the boxes marks the 25th percentile; the line within the boxes indicates the median; and the upper margin indicates the 75th percentile. The whiskers above and below the boxes indicate the 90th and 10th percentiles, respectively. The dots above and below the whiskers represent extreme outliers. **Indicates a highly significant difference ($p < 0.01$).

$Z = 1.624$, $p = 0.104$) (Fig. 5). In RAET, the median retrieval error ratio (RER) was 0.028 (range: 0.00–0.31), and in Polygon, it was 0.00 (range: 0.00–0.42). The median generalization error ratio (GER) in RAET was 0.083 (range: 0.00–1.00), and it was 0.00 (range: 0.00–1.00) in Polygon.

RTs did not differ significantly between the two paradigms either in the retrieval (Wilcoxon matched-pairs test $Z = 0.667$, $p = 0.505$) or the generalization (Wilcoxon matched-pairs test $Z = 0.595$, $p = 0.552$) parts of the test phase. The median RT in the retrieval part in RAET was 1840.71 ms (range: 1156.26–4046.87 ms), and 1763.73 ms in Polygon (range: 934.56–4036.71 ms). The median RT in the generalization part of RAET was 2127.58 ms (range: 1300.67–13075.50 ms), and it was 2450.20 ms in Polygon (range: 1048.25–823 0.50 ms).

DISCUSSION

The Rutgers Acquired Equivalence Test (RAET) was developed originally to dissociate the different phases of the visually guided associative learning of neurological patients with hippocampal and basal ganglia dysfunctions (Myers et al., 2003). Performance in the equivalence learning phase of the test provides information about the function of the frontostriatal loops, while performance in the test phase is assumed to rely on the hippocampi (Myers et al., 2003; Moustafa et al., 2009, 2010).

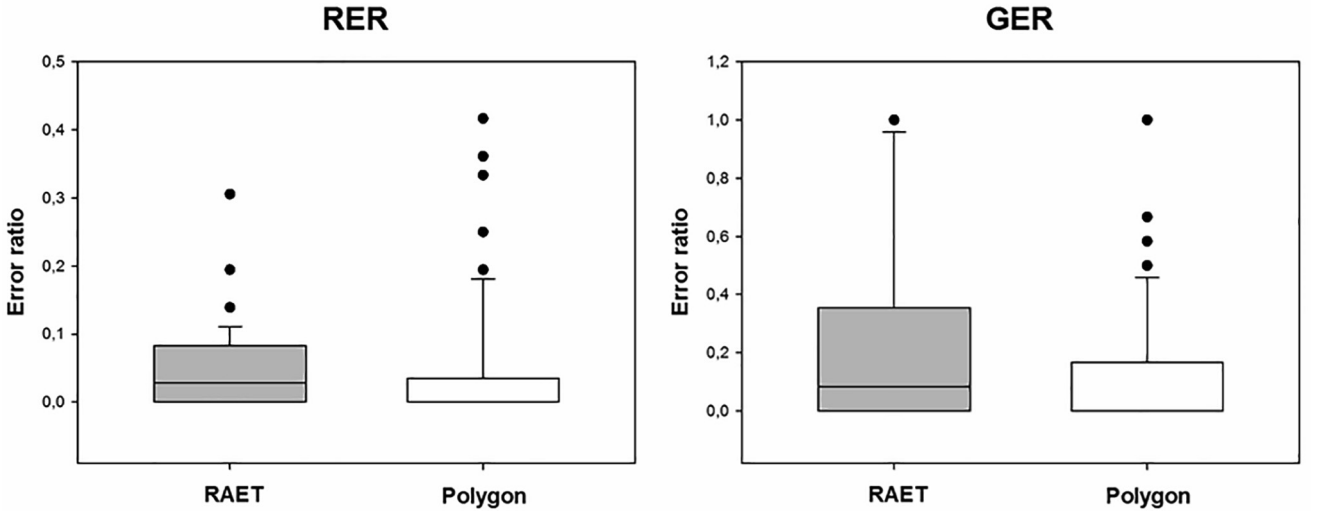

Fig. 5. Comparison of performances in the test phase of the two associative learning paradigms. RER: retrieval error ratio. GER: generalization error ratio. Otherwise, the conventions are the same as in Fig. 3.

The stimuli in the original version of RAET are human cartoon faces and colored fish. These are complex stimuli that contain various cues that can enhance association learning performance. In fact, having completed the tests, several participants were able even to verbalize the rule of association. During our long experience with RAET, we have never encountered a healthy volunteer who could not complete the test (Braunitzer et al., 2017; Eordegh et al., 2019). As for non-healthy populations, altered performance has been reported in certain conditions, but not in others (Myers et al., 2003; Keri et al., 2005; Bodi et al., 2009; Eordegh et al., 2020; Pertich et al., 2020; Giricz et al., 2021). Therefore, the sensitivity of this test is questionable in detecting mild changes in psychophysical performance. Having recognized this, we aimed to improve the sensitivity of this test, and developed a new visually guided equivalence learning test (Polygon). The new test is based on the principles of RAET, but it applies simple geometric shapes as stimuli instead of cartoon faces and fish. By this change, we sought to reduce the number of stimulus features to a minimum to avoid emotional responses or cognitive associations that could serve as extra cues for equivalence learning. To our knowledge, this is the first study to compare the visually guided equivalence learning performance of healthy volunteers across paradigms with stimuli of different complexity.

The basic structure of the two tests is very similar but there are some remarkable differences between them. In RAET, the antecedent stimuli are faces, each of which has three features (sex, age, and hair color). In contrast, antecedent stimuli in Polygon have only one feature, their shading (grayscale). Furthermore, the consequent stimuli in the RAET have only one distinctive feature, their color. In Polygon, the consequents have more than one distinctive features (such as the number of angles, sides or whether the stimulus points upward or downward). The primary aim during the construction of the stimuli in Polygon was to reduce the supporting information (emotional content, sematic content, and color information) to reduce the cortical contribution (Puszta et al., 2018; 2019) to the tasks. Additionally the more difficult task could be suitable to detect such weak differences, which were not detectable with the original RAET (Pertich et al., 2020; Giricz et al., 2021). It is true that in this respect, RAET and Polygon are not fully identical, but the modification of stimulus features allowed us to make the test more difficult (and sensitive) while keeping the original structure and logic. This way, the same testing paradigm is applied, but with stimuli that enable the detection of finer performance differences. Naturally, it would be possible to make the two tests even more similar, for instance, by using another set of consequent stimuli that would differ only in one feature.

As a preliminary analysis, we examined whether the order of the administration of the two tests was a significant factor of performance on the tests. We found no significant effect, which means that, at least in this study, the effects of learning, practice and fatigue can be excluded as confounding factors.

Our results showed that equivalence learning, which is linked primarily to the basal ganglia, is strongly influenced by the applied visual stimuli. The performance of the subjects was significantly weaker in the acquisition phase of Polygon than in the same phase of RAET, as indicated by the significantly higher error ratios and number of required acquisition trials. Based on working memory load, the acquisition phase can be divided into a low-load and a high-load part (Puszta et al., 2020). Since working memory load could influence the effectiveness of implicit learning (Collins and Frank, 2012), we also compared the subjects' performance in these two parts. The comparisons revealed that the performances in both the low- and high-load load parts of the acquisition phase were significantly better in RAET than in Polygon. In a recently published study (Eordegh et al., 2019), we administered a unimodal visual, a unimodal auditory, and an audiovisual version of the RAET paradigm to healthy subjects. We found no significant difference between the acquisition learning error ratios across the paradigms, which suggest that stimulus modality has no significant influence on performance in the acquisition phase. A possible explanation is that this type of feedback-based pair learning is a very old and conserved function, which is so simple that the different modalities contribute to the associative learning equally, and thus, the multisensory information has no priority in these learning processes. This is consistent with earlier findings that the basal ganglia, which predominate the acquisition phase of the associative learning test, are more active when rare stimulus associations appear, and this is not affected by stimulus modality (Amso et al., 2005). However, stimulus complexity and salience appear to be important determinants of learning effectiveness in sensory-guided equivalence learning. This is in agreement with the findings of previous studies, which demonstrated that stimulus complexity could influence auditory-guided associative learning, and more complex stimuli could elicit more accurate responses, better performance, and more prominent cortical activation (Brown and Proulx, 2013).

Reaction times in the acquisition phase were also significantly longer in Polygon, which shows that stimulus complexity affected this parameter as well. However, the longer reaction times did not result in performance improvement.

As for the error ratios in the retrieval and transfer (generalization) parts of the test phase, these did not differ between RAET and Polygon and neither did reaction times. In other words, stimulus complexity had no effect whatsoever on the retrieval of the previously learned associations and the transfer of the acquired rule of association to previously unseen stimulus pairs.

In summary, our results suggest that stimulus complexity can have a considerable influence on equivalence learning in healthy humans, but it has no or only a very weak effect on the connected memory processes (retrieval and transfer). The fact that the subjects made more mistakes in the acquisition phase of the Polygon can indicate that Polygon is a more sensitive test in healthy adults than the original RAET. If

this is true in basal ganglia-related neurological/psychiatric disorders as well, then Polygon could be a tool to detect fine learning alterations in such conditions that RAET is not capable of detecting. Upcoming studies should test this hypothesis.

CONTRIBUTIONS

A.N., Sz.K., B.B. and G.E. conceived the study conception and design. Data collection was made by K. T., A.H., A.L., Á.K., Á.H., and G.E.. Data analysis were performed by K.T., G.E., Á.K. and A.K. The manuscript was written by A.N., K.T. and G.E.. All authors discussed data analysis and interpretation. Funding acquisition was made by A.N. All authors reviewed/edited the manuscript and approved the final version.

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APPENDIX A. SUPPLEMENTARY DATA

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