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Estimation of Magnitudes and Numerosity in Different Formats of Stimulus Presentation: the Numerical Ratio Effect

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Abstract
Introduction. Several researchers discuss the possibility of existence of a common mental system responsible for the estimation of both discrete numerosities and continuous magnitudes. The numerical ratio effect observed during comparison tasks is one of the evidences of an existence of such system. It manifests itself in an increase in response time and a decrease in accuracy as the numerical proportion between the compared arrays of objects or magnitudes increases. This study investigated the numerical ratio effect for different types of tests and stimulus presentation formats in order to explore the interrelationships between systems of magnitude and numerosity estimation. **Methods.** The sample consisted of 83 students (20% were men, the average age was 20.34 years). The participants of the study performed nonsymbolic comparison tasks, arears comparison task and comparison of nonsymbolic quantity with symbolic numbers task (nonsymbolic – symbolic comparison test). Two formats of stimulus presentation were used during the nonsymbolic comparison test: separate/homogeneous and mixed/heterogeneous. The accuracy of estimation and numerical ratio effect were calculated for each test. **Results.** The numerical ratio effect was significant in the nonsymbolic comparison tests (for both formats of stimulus presentation) and in the nonsymbolic-symbolic comparison test, but was not significant in the areas comparison test. Numerical ratio effects for different tests do not correlate with each other. It was also shown that the accuracy of the estimation of magnitudes correlates with the results of the nonsymbolic comparison test, and this relationship was stronger for the mixed/heterogeneous format. **Discussion.** Results of this study demonstrated that the relationship between magnitude and discrete numerosity estimation systems can vary under different conditions of stimulus presentation. It makes possible to refine the existing theoretical models describing functioning of the Approximate Number System. The obtained results cannot be fully explained by the theory of a unified numerosity/magnitude estimation system. It was shown, however, that the magnitude estimation system does in fact contribute to the estimation of discrete numerosity.

Keywords: the Approximate Number System, number sense, the Approximate Magnitude System, nonsymbolic representation, numerical ratio effect, congruency effect, visual cues, nonsymbolic comparison, format of stimuli presentation

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Introduction

Starting from a very young age, humans are able to perceive and process "quantitative" information. For example, people can estimate and compare distances to surrounding objects, compare objects by size (length, width, height, area) or determine which arrays contain more objects. During evaluation and processing of "quantitative" information, there are three main dimensions that can be estimated: time (for example, estimation of temporal periods), space (estimation of sizes, lengths, distances, areas, etc.) and numerosity (estimation of the number of discrete objects). It should be noted that estimation of numerosity refers to the ability to estimate the discrete characteristics of objects, while estimation of size or time is described as the estimation of continuous magnitudes (Leibovich & Henik, 2014).

Several researchers proposed the existence of a single unified system responsible for the estimation of both numerosity and magnitude (Walsh, 2003). This so called General Magnitude System (GMS) is part of the proposed theory - A Theory of Magnitude (ATOM). Currently, there are a fairly large number of studies confirming the existence such system. Firstly, a large number of neurophysiological studies have shown that the right intraparietal sulcus is activated when processing information about quantity, time, and size (e.g., Bueti & Walsh, 2009; Dormal & Pesenti, 2007; Dormal, Andres & Pesenti, 2012). For example, electrical stimulation of this brain area was shown to lead to changes in both quantity and time and length perception (Cappelletti et al., 2013; Dormal et al., 2012).

Secondly, in studies related to the processing of numerosity without using symbols (Approximate Number Sense, ANS), it was shown that an approximate and quick estimation of numerosity was predominantly based on the evaluation of continuous visual properties, such as the size of objects, total area, perimeter of the occupied surface (convex hull), density (Gebuis & Reynvoet, 2012; Hurewitz, Gelman, & Schnitze, 2006; Clayton, Gilmore & Inglis, 2015). For example, when comparing the number of objects in two arrays, the numerosity decision could be based on comparison of sizes of the objects, surface areas, or cumulative areas. The estimation of numerosity can be based on processing of information related to several visual parameters (e.g. Gebuis, Kadosh, & Gevers, 2016; Leibovich, Katzin, Harel & Henik, 2017). Many studies have confirmed that the estimation of numerosity was more accurate in congruent conditions, when visual parameters provided the correct information related to numerosity, compared to incongruent conditions (e.g. Smets, Moors & Reynvoet, 2016; Clayton, Gilmore & Inglis, 2015). For example, when a set containing more objects had a larger surface or cumulative area than a set, containing fewer objects. Differences between congruent and incongruent items (the congruency effect) reflect the bias in numerosity estimation that is related to estimation of visual cues.

Additionally, some researchers have suggested that there is no separate ability (or a system) responsible for nonsymbolic estimation of numerosity, since it is always related to estimation of continuous visual parameters (for example, Gebuis & Reynvoet, 2012). Some studies have shown that a person can identify differences or changes in numerosity only if they are accompanied by differences or changes in visual cues (e.g. Gebuis, Kadosh & Gevers, 2016). Other researchers have proposed "softer" hypotheses, suggesting that the estimation of numerosity can be be both direct and indirect via the estimation and comparison of numerous visual cues (for example, Kuzmina & Malykh, 2022; Leibovich-Raveh, Stein, Henik & Salti, 2018). It was also shown that the estimation of numerosity can, in turn, distort the estimation of physical dimensions (e.g., Leibovich, Henik, & Salti, 2015; Hendryckx, Guillaume, Beuel, Van Rinsveld & Content, 2021).

The existence of a united system responsible both for the estimation of numerosity and continuous magnitudes (such as length or area) is evidenced by the fact that patterns observed during quantity comparison tasks are also observed in tasks related to comparison of physical dimensions. In particular, the numerical ratio effect (NRE), an increase in response time and a decrease in accuracy as the ratio between two compared arrays of objects becomes smaller, was found when comparing the lengths of segments (Dormal & Pesenti, 2007), the number of objects (Sasanguie, Defever, Van den Bussche & Reynvoet, 2011) and comparing numbers (Lyons, Nuerk & Ansari, 2015). According to numerous findings, NRE reflects the important characteristic of numerosity processing and is associated with the overlapping of neuron activation curves for processing numerositites which are closer to each other (Dehaene, 2003; Dietrich, Huber & Nuerk, 2015). Observing the NRE for both discrete objects comparison tasks and continuous objects comparison tasks may confirm the existence of common system that is responsible for the estimation of both the numerosity and magnitude.

On the other hand, there exists some findings that contradict the proposed theory (A Theory of Magnitude). Some studies have shown that visual and quantitative information can be processed independently of each other (Park, DeWind, Woldorff & Brannon, 2016; Odic & Halberda, 2015). Several other studies have also shown that humans have the ability to estimate numerosity directly, similarly how other perceptual properties such as the volume, size, shape of objects, etc. are estimated (Ross & Burr, 2010; Sokolowski, Fias, Mousa & Ansari, 2017). Dedicated "numerical" neurons in the right intraparietal sulcus are responsible for this specific sensitivity to quantitative information (for example, Nieder & Miller, 2003; Piazza, Pinel, Le Bihan & Dehaene, 2007; Nieder, 2016). A number of studies have also demonstrated that "quantity" can be processed independently in the visual cortex during early stages of perception, similarly to the way low-level visual information is processed (Fornaciai, Brannon, Woldorff & Pa, 2017; Van Rinsveld et al., 2020).

Secondly, recent data from psychophysiological studies and simulation studies using neural networks and deep learning models showed that the quantity estimation and the estimation of visual parameters can be closely interrelated during the early stages of development, but during later stages of development estimation of numerosity can be carried out independently of estimation of visual cues (Testolin , Zou & McClelland, 2020; Creatore, Sabathiel & Solstad, 2021).

It was hypothesized that numerosity could be estimated both directly and indirectly through the estimation of visual parameters (Kuzmina & Malykh, 2022; Kuzmina et al., 2019). At the same time, numerosity comparison might be affected by the formats of stimulus presentation and the availability of visual cues. It was shown that in the case of easy access to comparison of visual cues such as surface area or cumulative area (e.g. in the case of separated/homogeneous format where two sets of identical figures are presented together, but they are still separated spatially), the estimation of quantity can be distorted by the assessment of visual parameters, which manifests in an increase in the congruency effect (Kuzmina & Malykh, 2022; Kuzmina et al., 2019; Kuzmina et al., 2020). The congruency effect becomes insignificant, and the comparison numerosities becomes less biased when comparison of certain visual cues are impended (for example, during comparison of two sets of heterogeneous objects without an obvious spatial separation, i.e. in a mixed/heterogeneous presentation format).

Although several studies have shown that the accuracy of nonsymbolic comparison can vary depending on the format of stimulus presentation (e.g., Price, Palmer, Battista & Ansari, 2012) and that corresponding congruency effects varied for different formats (Kuzmina & Malykh, 2022), the association between accuracy of estimation of continuous magnitudes with accuracy of nonsymbolic comparison in different formats of presentation in unclear.

The current study has two main goals. The first goal is to assess the NRE in magnitude comparison task and in nonsymbolic numerosity comparison task in two formats of stimulus presentation. NRE is a key characteristic of representation of quantity in different formats, so we assume that if there is a single system responsible for quantity estimation for both continuous and discrete quantities, there should be a high correlation between the NREs in magnitude comparison and in numerosity comparison, regardless of the format of stimulus presentation.

The second goal is to assess the contribution of the accuracy of the magnitude comparison and numerosity estimation to the performance of tasks for nonsymbolic comparison in different formats. We assume that the accuracy of the magnitude comparison will be more related to the accuracy of the nonsymbolic comparison in the format that produces larger congruency effect, while the accuracy of the discrete numerosity estimation is more related to the accuracy of the nonsymbolic comparison in the format in which the congruency effect is smaller.

Method

Sample

The sample consisted of 92 students (mean age 20.36 years, standard deviation 5.33 years, 20% were men). Nine participants failed to complete at least one of the tests, so they were excluded from the final analysis. The demographic characteristics of the sample did not change after the exclusion. The final sample included 83 people (20% men, mean age 20.34 years).

Procedure and instruments

The study was conducted using the online pavlovia.org platform. Participants were asked to complete three tests: a nonsymbolic comparison test, an areas comparison test, and a numerosity estimation test (comparison of number of objects with symbolic numerosity).

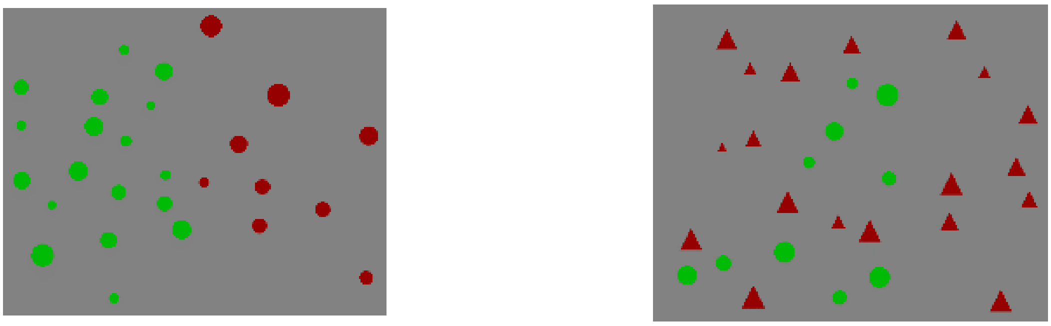
Nonsymbolic comparison test

During the test, two sets of red and green figures (circles of triangles) were demonstrated to a participant, who was supposed to determine if there were more green or red colored figures on the screen and press the corresponding key: "r" - if there were more red ones, "g" - if there were more green ones. Both sets of figures were demonstrated on the screen for 400ms, after which the reminder was shown: "Press “r” if there are more red figures, press “g” if there are more green figures." After the key was pressed, a fixation cross was shown on the screen (400 ms) and then the next screen with two sets of figures was demonstrated.

Two formats of stimulus presentation were used in the test: a separate format with homogeneous figures and a mixed format with heterogeneous figures (Figure 1).

Figure 1

Examples of formats of stimulus presentation



A. Separate/homogenous B. Mixed/heterogenous

Both formats were chosen based on the data from previous studies that have shown that the separate/homogeneous format produces the largest congruency effect, indicating that the numerosity estimation might be distorted by the estimation of visual cues. In the mixed/heterogeneous format, the congruency effect was not significant (Kuzmina et al., 2019; Kuzmina et al., 2020; Kuzmina & Malykh, 2022).

Two types of numerical proportions were included for each presentation format: simple and complex proportion. For a simple proportion, the ratio of a smaller array of objects to a larger one varied from 0.47 to 0.53 (a smaller numerosity divided by a larger one), for a complex proportion it varied from 0.72 to 0.77. The choice of ratio was based on the data from previous studies, which demonstrated, for example, that with a ratio of 0.5, accuracy of comparison approaches 0.90 on average, but as the ratio increases, the accuracy decreased significantly. For a ratio of 0.75, accuracy ranged from 0.72 to 0.80, depending on the format of stimulus presentation (Price et al., 2012).

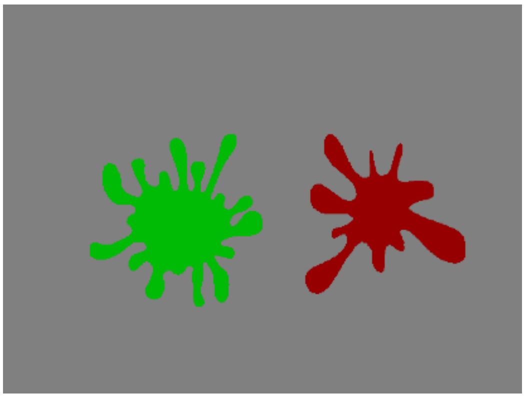
In half of trials the stimuli shown were congruent on two visual parameters - the convex hull (the perimeter of the area that includes all figures of the same color) and the total area (the sum of the areas of all figures of the same color) - for each type of proportion and format of presentation. In the other half, the stimuli were incongruent on the same parameters. There were 216 tasks in total. Stimuli from different conditions were randomly mixed, the order of presentation was the same for all respondents.

Areas Comparison Test

Each participant was presented with two figures ("blobs") of red and green colors on the screen (Figure 2). Similarly to the nonsymbolic comparison test, the "blobs" were presented for 400 ms, after which the participant was supposed to choose a figure with a larger total area by pressing then corresponding key: "r" if the larger figure was red or "g" if it was green.

Figure 2

Areas comparison test stimulus example



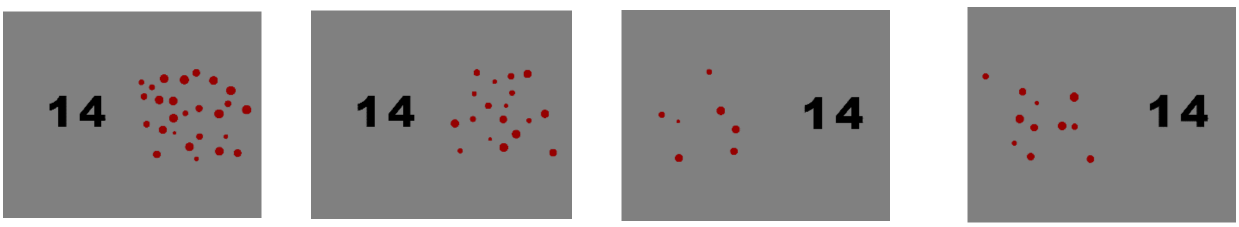
Two additional conditions were also added to the test: a simple and a complex proportion of total areas of the two figures. The ratios of areas of the two figures varied from 0.47 to 0.53 for simple proportion, and from 0.72 to 0.77 for complex proportion. The ratios were chosen to be comparable to the conditions of the nonsymbolic quantity comparison task. In total, there were 124 tasks in the test.

Numerosity Estimation Test

The respondents were presented with a screen showing a number on one side and an array of geometric shapes (circles or triangles) on the other (Figure 3). The respondent had to choose which side of the screen represented a greater number - the number shown or the amount of geometric shapes shown - by pressing the corresponding key: "right arrow" if a greater number was represented by information on the right side of the screen or "left arrow" in the other case.

Figure 3

Numerosity estimation example stimulus material (number and quantity comparison)



A. Simple proportion, quantity greater than number

B. Complex proportion, quantity greater than number

C. Simple proportion, number greater than quantity

D. Complex proportion, number greater than quantity

Two-digit numbers from 10 to 16 were used in the test. The tasks were designed in such a way that in half of the cases the number was greater than the amount of figures and vice versa in the other half. The side of the screen that showed either the number or the shapes was controlled. Thus, in 25% of the tasks the number was greater and it was shown on the left, in 25% of the tasks the number was smaller and it was shown on the left, in 25% of the tasks the number was greater and it was shown on the right, in 25% of the tasks the number was smaller and it was shown on the right.

Similarly to the previous tests, the proportion between the number and the amount of figures shown could be simple (ratio from 0.50 to 0.55) or complex (ratio from 0.70 to 0.78). A total of 56 tasks were included in the test.

Statistical approach

At the first step of analysis, the accuracy was calculated for each test (the proportion of correct answers). At the next step, the NRE was calculated for the area comparison and numerosity estimation tests and for the two formats of stimulus presentation of the nonsymbolic comparison test. The NRE was calculated as the difference in accuracy between items with a simple proportion and items with a complex proportion. The NREs were calculated for each respondent and then the correlations between the NREs in three tests were evaluated.

Next, a regression analysis was performed for the accuracy of nonsymbolic comparison in both formats of stimulus presentation as a dependent variable. For each dependent variable (accuracy in separate/homogeneous format and accuracy in mixed/heterogeneous format), the accuracy of the area comparison and the accuracy of the numerosity estimation (comparison of number and quantity) are included as predictors into the model. The comparison of standardized regression coefficients provided information about effect size of association of each predictor with dependent variables.

Results

Descriptive statistics

Table 1 shows test accuracy scores, standard deviation, and range.

Table 1

Descriptive statistics for area comparison, numerosity estimation, and nonsymbolic comparison tests

Tests	Accuracy (ratio of correct answers)			
	Average (s.e.)	SD	Min	Max
Area comparison	0.82 (0.01)	0.12	0.48	0.94
Numerosity estimation	0.80 (0.01)	0.13	0.45	1
Nonsymbolic comparison (separate/homogenous format)	0.84 (0.01)	0.10	0.54	0.97
Nonsymbolic comparison (mixed/ heterogenous format)	0.83 (0.01)	0.10	0.49	0.96

In general, it should be noted that the accuracy was quite high for all tests. The lowest average accuracy was observed in numerosity estimation test, which involved the comparison of a number and a quantity of geometric objects.

At the next step, an analysis of differences in accuracy between simple and complex proportions was carried out for each test. Mean differences and their statistical significance are presented in Table 2.

Table 2

Analysis of differences in accuracy between simple and complex proportions for area comparison, numerosity estimation and nonsymbolic comparison tests

Test	Simple proportion	Complex proportion	Proportion effect [95 % CI]	t-test
Area comparison	0.81	0.82	-0.01 [-0.02; 0.002]	-1.69
Numerosity estimation	0.84	0.81	0.03 [0.01; 0.05]	3.05**
Nonsymbolic comparison (separate format)	0.89	0.72	0.17 [0.15; 0.19]	18.07***
Nonsymbolic comparison (mixed format)	0.91	0.74	0.17 [0.15; 0.18]	22.20***

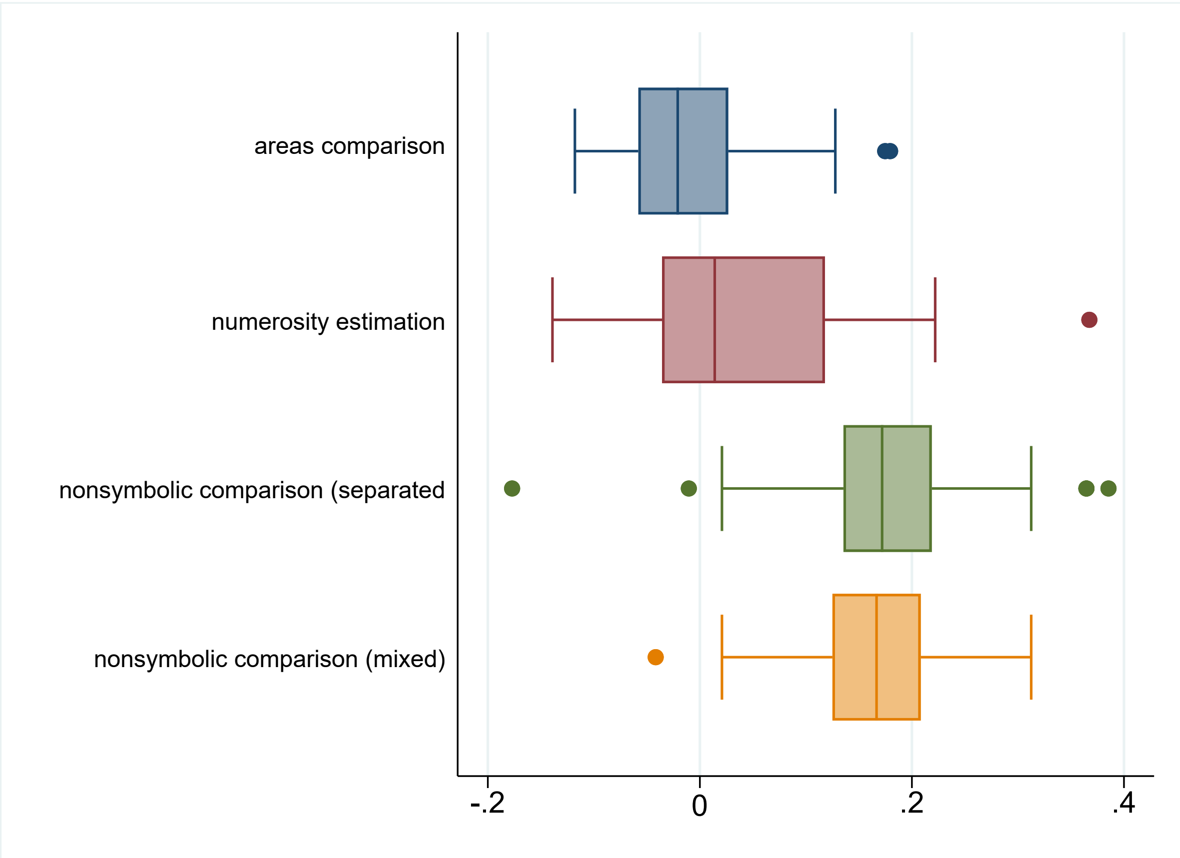
*Note: ***p<,001, **p<,01*

An analysis of the average NRE for each test showed that in the areas comparison test, the NRE was not significant. In the numerosity estimation test, the NRE was significant but small. For both formats of the non-symbolic comparison test, the NRE was identified and the effect size is significant (Cohen's d = 1.62 for the mixed format and 1.66 for the separated format).

Next, to analyze the relationship between NREs in different tests, the NREs were calculated for each respondent. The distribution of NREs for three tests are shown at Figure 4.

Figure 4

Numerical ratio effect (difference in performance between simple and complex proportions) for different tests and conditions of stimuli presentation



Next, correlations between NREs for different tests were analyzed. The analysis showed that NREs do not correlate with each other, with one exception. There was a significant negative correlation between the NRE in the area comparison test and the NRE in the nonsymbolic comparison test in separate/homogeneous format ($r = -0.31$, $p=0.005$). Thus, higher NRE in the nonsymbolic comparison test are associated with lower NRE in the area comparison test.

During the final stage of the analysis, a regression analysis was performed for the accuracy of the nonsymbolic comparison in each format as a dependent variable. The results of the regression analysis are presented in Table 3.

Table 3

Results of the regression analysis of the relationship between the accuracy of nonsymbolic comparison test and the accuracy of numerosity estimation and area comparison

Variables	DV: Accuracy in separated format		DV: Accuracy in mixed format	
	B (s.e.)	β	B (s.e.)	β
Constant	0.41*** (0.06)		0.35*** (0.06)	
Accuracy of area comparison	0.30** (0.09)	0.37	0.43*** (0.08)	0.52
Accuracy of estimation of numerosity	0.23** (0.07)	0.33	0.16* (0.07)	0.22
F-test	23.73		30.25	
R-squared	0.36		0.42	

*Note: ***p< .001, ** p<.01, *p<.05*

The results of the analysis showed that the accuracy of areas comparison was significantly associated to the accuracy of nonsymbolic comparison for both formats of stimulus presentation. Additionally, this relationship was stronger for the mixed format of presentation, compared to the separate format. The accuracy of the estimation of numerosity was also related to the accuracy of the nonsymbolic comparison, although the effect of area comparison was stronger. The results obtained partly contradict the previously suggested hypotheses, which will be discussed below in the "Discussion" section.

Discussion

In this study, we examined the accuracy and the NRE for three different tests designed to the assess the ability to estimate quantitative information. Previous studies explore the extent to which the estimation of sets of discrete objects (numerosity) and the estimation of continuous quantities (magnitudes) can be related. It was suggested that the estimation of numerosity without using of symbols can be carried out both directly (direct estimation of numerosity) and indirectly, through the estimation of visual parameters (Kuzmina et al., 2019; Kuzmina & Malykh, 2022). Additionally, the choice of the estimation approach used may be determined by the format of stimulus presentation (separate or mixed).

The current study tested the hypothesis that the accuracy of nonsymbolic comparison in a separate presentation format correlates more strongly with the accuracy of magnitude comparison (assessed using the areas comparison test), while the accuracy of the numerosity estimation (assessed using the symbolic-nonsymbolic comparison test) correlates more strongly with the accuracy of nonsymbolic comparison in mixed format. In addition, the NRE was assessed for all tests and the correlation of proportion effects was evaluated for all tests and formats of stimulus presentation.

The results show that the NRE is more pronounced in the nonsymbolic comparison test and is not significant in the magnitude comparison test (e.g., Leibovich & Henik, 2014). This contradicts, in part, previous findings regarding NRE in magnitude comparison tests. Consideration of the conditions of previous studies may explain these discrepancies. Leibovich & Henik (2014) used an area comparison task with squares, while our study used blobs instead areas. It seems that, in general, comparison of areas of complex figures is more complicated process than comparison of squares, when for area comparison it is enough to compare the length of one or two sides. Additionally, only two types of numerical proportion ranges were used in our study (simple, ranging from 0.47 to 0.53 and complex, ranging from 0.72 to 0.75), while other studies used more types of ranges and more complex proportions (for example, ranging from 0.80 to 0.95). In the study by Leibovich & Henik (2014), it was shown that the decrease in accuracy associated with increase in proportion during area comparison tasks manifested only for the most complex proportion (greater than 0.85), less complex proportions showed no decrease in accuracy. Taking this into account, we can conclude that during estimation of continuous parameters, the NRE is observed only in the conditions of significantly more complex proportions than those used in our study.

This study revealed that there were no significant correlations between the NRE for different tests, with a single exception. On one hand, this may serve as evidence that the systems of representation of discrete numerosity and the representation of continuous magnitudes are separate systems, which was also confirmed in previous studies (for example, Odic, 2018; Leibovich & Henik, 2014). On the other hand, the absence of correlations can be explained by the specificity of evaluation of the NREs. The NRE was obtained as the difference in accuracy between the complex and simple proportions. Previously, some studies have shown that the NRE has low reliability and low variance (e.g., Lyons et al., 2015; Maloney, Risko, Preston, Ansari & Fugelsang, 2010; Chesney, 2018). Additionally, any parameter calculated as the difference between two conditions was shown to have lower reliability than the parameter obtained in any of the separate condition (Caruso, 2004).

The results of the regression analysis did not confirm the proposed hypothesis. On the one hand, the accuracy of area comparison is strongly related to the accuracy of nonsymbolic comparison in both formats of stimulus presentation. Secondly, it is more strongly related to nonsymbolic comparison in mixed format, which contradicts the proposed hypothesis. On the other hand, the results obtained may indicate that the estimation of visual parameters is involved in the estimation of quantity, regardless of the format. Still, it was shown previously that in a mixed presentation format, participants are less reliant on the assessment of the surface area or the convex hull, and rely more on the assessment of the cumulative area (the sum of the areas of all objects). The cumulative area effect was observed even for heterogeneous objects, although in general it is more difficult to estimate the cumulative areas in this case (Kuzmina et al., 2020; Kuzmina & Malykh, 2022). It may possible that in the current version of the test in this study, the comparison of areas was based on the estimation of the cumulative area, rather than the perimeter. The compared figures had complex shapes, so assessment and comparison of perimeters can be difficult in this case. In a separate presentation format, as shown in previous studies, participants rely more on the assessment of the perimeter or the convex hull, the assessment of which was not required in the area comparison test due to the peculiarity of figures involved in the test. Taking this into account, in future studies it might be necessary to alter the area comparison tasks accordingly. Firstly, more complex types of proportions should be used for visual parameter comparison tasks. Secondly, different types of figures (shapes) should be used in order to assess the participants ability to compare convex hulls, and not only cumulative areas.

Weak correlation of numerosity estimation test accuracy with the accuracy of nonsymbolic comparison is also difficult to explain. One possible explanation is that comparison of symbolic and nonsymbolic numerosity required the mapping ability, the ability to map nonsymbolic representations of quantity to symbolic representations. The mapping implies the involvement of the system of symbolic representation. According to some studies, the systems of symbolic representation and the system of nonsymbolic representation are separated and the relationship between them reduced across development (for example, Lyons, Nuerk, & Ansari, 2015; Sasanguie, De Smedt, & Reynvoet, 2017; Goffin & Ansari , 2019). Taking into account that participants were students, one possible explanation is the weakening of the connection between the symbolic and nonsymbolic systems of representation at this age, which is reflected in lower involvement of the symbolic system in nonsymbolic comparison. In other words, when comparing two sets of objects, participants do not need to convert a nonsymbolic quantity into its symbolic representation, they can compare sets based on their visual parameters or directly estimate the numerosity.

It should also be noted that small sample size is one of the limitations of this study, which could lead to a decrease in its statistical power and an increase in the probability of Type I error (Schönbrodt & Perugini, 2013; Akobeng, 2016). In future studies, it is necessary to investigate the findings obtained in this study on a larger sample and take into account the possibility of improving the design of the tests.

Conclusion

- The NRE is more pronounced in the nonsymbolic comparison test and is not significant in the area comparison test.
- There are no significant correlations between the NRE for area comparison test, numerosity estimation test, and nonsymbolic comparison test, which do not confirm the hypothesis of existence of a common for processing both discrete numerosity and continuous magnitude.
- The accuracy of comparison of visual parameters correlates with the accuracy of nonsymbolic comparison, and this relationship is more pronounced for the mixed/heterogeneous format of stimulus presentation.

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Conflict of interest information
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