Received: 4 January 2022 | Revised: 18 August 2022 | Accepted: 10 November 2022

DOI: 10.1111/desc.13347

Developmental Science WILEY

RESEARCH ARTICLE

Infants' sense of approximate numerosity: Heritability and link to other concurrent traits

Charlotte Viktorsson[1] | **Marcus Lindskog**[2] | **Danyang Li**[3,4] | **Kristiina Tammimies**[3,4] | **Mark J. Taylor**[5] | **Angelica Ronald**[6] | **Terje Falck-Ytter**[1,3,7]

[1]Development and Neurodiversity Lab, Department of Psychology, Uppsala University, Uppsala, Sweden

[2]Uppsala Child & BabyLab, Department of Psychology, Uppsala University, Uppsala, Sweden

[3]Center of Neurodevelopmental Disorders (KIND), Division of Neuropsychiatry, Department of Women's and Children's Health, Karolinska Institutet, Stockholm, Sweden

[4]Astrid Lindgren Children's Hospital, Karolinska University Hospital, Region Stockholm, Sweden

[5]Deptartment of Medical Epidemiology & Biostatistics, Karolinska Institutet, Stockholm, Sweden

[6]Department of Psychological Sciences, Birkbeck, University of London, London, UK

[7]Swedish Collegium for Advanced Study, Uppsala, Sweden

Correspondence
Charlotte Viktorsson, Department of Psychology, Uppsala University, Von Kraemers allé 1A, 751 42 Uppsala, Sweden.
Email: charlotte.viktorsson@psyk.uu.se

Funding information
Riksbankens Jubileumsfond, Grant/Award Numbers: NHS14-1802, 1; Knut and Alice Wallenberg Foundation; Swedish Research Council, Grant/Award Number: 2018-06232; HORIZON EUROPE Marie Sklodowska-Curie Actions, Grant/Award Number: MSCA-ITN-2018N.81

Abstract

The ability to perceive approximate numerosity is present in many animal species, and emerges early in human infants. Later in life, it is moderately heritable and associated with mathematical abilities, but the etiology of the Approximate Number System (ANS) and its degree of independence from other cognitive abilities in infancy is unknown. Here, we assessed the phenotypic specificity as well as the influence of genetic and environmental factors on the ANS in a sample of 5-month-old twins ($N = 514$). We found a small-to-moderate but statistically significant effect of genetic factors on ANS acuity (heritability = 0.18, 95% CI: 0.02, 0.33), but only when differences in numerosity were relatively large (1:4 ratio). Non-verbal ability assessed with the Mullen Scales of Early Learning (MSEL) was found to be heritable (0.47; 95% CI: 0.34, 0.57) and the phenotypic association between ANS acuity and non-verbal ability performance was close to zero. Similarly, we found no association between ANS acuity and general attention during the task. An unexpected weak but statistically significant negative association between ANS acuity and scores on the receptive language scale of the MSEL was found. These results suggest that early ANS function may be largely independent from other aspects of non-verbal development. Further, variability in ANS in infancy seems to, to some extent, reflect genotypic differences in the population.

KEYWORDS
ANS, approximate number system, development, infancy, non-verbal ability, twins

Highlights

- Assessing 514 infant twins with eye tracking, we found that infants' sense of approximate numerosity is heritable and not positively associated with concurrent attentional, cognitive or motor abilities.
- These results have implications for our understanding of development of mathematical ability and the link between cognitive abilities early in postnatal life.

1 | INTRODUCTION

The Approximate Number System (ANS) is believed to be dedicated to the perception of approximate numerosity, without relying on language or symbols (Feigenson et al., 2004). The ability to differentiate between approximate numerosity increases during the first year of life in human infants (Xu et al., 2005) and stable individual differences emerge (Libertus & Brannon, 2010). The ANS has also been found in non-human animals (Boysen & Hallberg, 2000; Kilian et al., 2003), suggesting an evolutionary importance of the ANS (Halberda et al., 2008). In older children and adults, ANS acuity is typically measured by comparing simultaneously presented stimuli, such as quickly flashing dots, asking the participants which group of stimuli contained more objects (i.e., dots in this example; Odic & Starr et al., 2018). In this case, the ANS acuity of a specific individual is usually defined as the smallest ratio that the individual can reliably discriminate (Odic & Starr, 2018). In infants, ANS is usually measured by habituation paradigms, or by preferential looking to one of two simultaneously presented streams of dots (one having the same number of dots and one changing in numerosity). In this study, we used the preferential looking paradigm, where the ANS score reflects the preference for looking at the numerically changing stream. The ANS score has been called both ANS accuracy and ANS acuity in the previous infancy literature (with small variations in measurement and definition); we will use the term ANS acuity throughout this paper.

Several studies have found an association between ANS acuity and concurrent mathematical ability in both childhood (Schneider et al., 2017) and adulthood (Chen & Li, 2014). However, the nature of the association between the ANS and formal math ability is currently debated. One study found that ANS acuity in adolescence correlated with earlier mathematical skills even when controlling for a wide range of cognitive abilities (Halberda et al., 2008), suggesting that the ANS is an independent cognitive skill associated with mathematical ability. Although it has been argued that inhibitory control drives the association between ANS acuity and mathematical achievement in childhood (Fuhs & McNeil et al., 2013; Gilmore et al., 2013), several studies have found a significant association even when controlling for inhibitory control in various setups (Keller & Libertus, 2015 ; Lindskog et al., 2021; Malone et al., 2019). A longitudinal study found that ANS acuity in adolescence was predicted by reading and spatial ability in childhood (Tosto et al., 2017), supporting the view that the ANS is not a numerical-specific process. Few studies have investigated the association between the ANS and other cognitive measures in infancy, but Libertus & Brannon (2010) found that ANS acuity at 6 months did not predict visual short-term memory at 9 months.

A modest genetic influence on individual differences in ANS acuity has been found in late childhood (Lukowski et al., 2017) and adolescence (Tosto et al., 2014). With regards to specificity, Lukowski et al. (2017) found that ANS acuity has a genetic overlap with mathematical ability and general cognitive skills. The overlap with general cognitive skills accounted for the majority of the genetic influence on mathematical ability. This result is in line with genetic studies of cognition in older children and adults showing that even seemingly dissimilar traits typically show a large degree of genetic overlap. For example, genetic factors associated with mathematical ability largely overlap with those involved in reading (Plomin & Kovas, 2005), presumably reflecting so-called generalist genes, which exercise broad effects on many different cognitive functions (Kovas & Plomin et al., 2006). However, whether this general pattern also applies to early infancy is not established. Qualitatively different cognitive skills may become correlated over development, despite reflecting separate processes (with potential separate etiological influences) in infancy (van der Maas et al., 2006).

The primary aim of this study was to establish the genetic and environmental contribution to ANS acuity in early infancy and to investigate the degree of independence from other early-emerging abilities. We used the paired visual preference paradigm, previously employed when studying the ANS in infants (Libertus & Brannon, 2010; Libertus et al., 2014; Schroder et al., 2020; Starr & Brannon, 2015). Given the findings in previous studies (Lukowski et al., 2017; Tosto et al., 2014) we expected to find a modest genetic contribution to ANS acuity. Moreover, we examined the association between ANS acuity and non-verbal ability, consisting of fine motor, gross motor, and visual reception tasks. These abilities were chosen based on the developmental stage of the participating infants. At five months of age, there is a limited number of cognitive abilities that are measurable, and these are among the first abilities that emerge. We expected the association between ANS acuity and non-verbal ability to be positive, given that different cognitive abilities generally are associated. As a control for general attention during the experiment, we also examined the association between ANS acuity and looking time at screen.

2 | METHODS AND MATERIALS

2.1 | Participants

The initial sample consisted of 622 same-sex twins (311 pairs). Same-sex twin families in the greater Stockholm area were identified via the Swedish Population Registry (Folkbokföringsregistret, hosted by the Swedish Tax Agency). In total, 1068 families with same-sex twins were invited to join the study via letters, of which 311 families (29%) participated in the study. The pre-specified target sample size was 620 individuals (310 pairs) based on the size of previous twin studies of toddlers (e.g., Ronald et al., 2010). The experiment was a part of the Babytwins Study Sweden (BATSS; Falck-Ytter et al., 2021), and data collection was performed at the Centre of Neurodevelopmental Disorders at Karolinska Institutet. Informed consent was obtained from the parents of all the twins who participated. The study was approved by the regional ethics board in Stockholm and was conducted in accordance with the Declaration of Helsinki.

The infants were tested at the age of 5 months (for descriptive statistics, see Table 1). During the visit, the twins performed different tasks at the same time, in separate rooms. Among the recruited and tested infants, three twins were excluded from analysis due to seizures ($n = 2$ infants) and spina bifida ($n = 1$ infant). In addition, for this analysis

TABLE 1 Descriptive statistics

	N		Mean (SD)					
	MZ	DZ	MZ males	MZ females	DZ males	DZ females	Skewness	Kurtosis
***N* females (%)**	128 (45.7%)	117 (50.0%)	–	–	–	–	–	–
Age (in days)[a]	–	–	167.0 (8.1)	168.0 (9.0)	167.6 (9.5)	168.1 (8.6)	0.56	0.41
Parental education[b]	280	234	3.26 (0.77)		3.33 (0.71)		−0.71	−0.75
Family income[c]	273	223	6.38 (2.30)		6.83 (2.38)		−0.22	−0.85
1:4 ratio condition[d]	280	234	65.26 (13.0)	64.95 (11.7)	64.43 (11.4)	65.81 (12.0)	−0.20	−0.17
MSEL[e] **(non-verbal)**	311	249	137.93 (13.83)	138.74 (15.90)	140.07 (15.68)	142.48 (17.30)	0.32	0.09
Gross motor	-	-	47.43 (6.73)	47.30 (7.53)	47.85 (7.83)	48.31 (7.63)	−0.18	0.72
Fine motor	-	-	44.15 (7.29)	45.14 (7.12)	45.32 (7.49)	46.57 (8.04)	0.35	0.21
Visual reception	-	-	46.45 (6.50)	46.62 (6.80)	47.02 (6.24)	47.60 (6.70)	0.50	1.45

[a] Four twin pairs differed in age due to being born on different days (three pairs) or being tested on different days (one pair), in these cases the mean age was used.

[b] Education level on a scale from 1 to 4, where 1 = Primary, 2 = Secondary, 3 = Undergraduate ($\leq$3 years) and 4 = Postgraduate level (> 3 years).

[c] Family income per month. Scale 1–10 where 1 = < 20K, 2 = 20–30K, 3 = 30–40K, 4 = 40–50K, 5 = 50–60K, 6 = 60–70K, 7 = 70–80K, 8 = 80–90K, 9 = 90–100K and 10 = > 100K (SEK).

[d] Ratio of looking at the numerically changing side, averaged for all trials in the 1:4 ratio condition.

[e] MSEL = Mullen Scales of Early Learning. The subscales are reported as T-scores, and the non-verbal scale is reported as the sum of the T-scores from the three subscales.

we excluded infants due to twin-to-twin transfusion syndrome (n = 12 twin pairs) and birthweight below 1.5 kg (n = 1 infant). Some infants did not provide any data due to technical reasons (n = 2 twin pairs + 1 infant), lack of time (n = 3 twin pairs + 1 infant), infant being too tired or fussy (n = 4 infants), or lack of room (n = 1 twin pair). Moreover, infants were excluded if they did not have at least four valid trials (see Measures section for details). Due to invalid trials, 62 infants were excluded. The final sample consisted of 514 infants. There were no statistically significant differences between the excluded and included infants regarding age, sex, family income, or parental education. Sample demographics are fully reported elsewhere (Falck-Ytter et al., 2021).

2.2 | Stimuli and measures

Gaze data was recorded using the Tobii T120 Eye-tracker with a sampling rate of 60 Hz, using a standard Tobii monitor at native resolution (1024 × 768). The infant was seated in a baby chair or in the parent's lap, at a distance of approximately 60 cm from the screen. A five-point calibration image was used to determine the positions of the eyes, and the experimental task did not begin until a successful calibration was achieved. Another five-point video for offline calibration validation purposes was shown once in the beginning of the eye-tracking session. These data were evaluated via ocular inspection, and a simple linear transformation of data was performed when necessary (using custom MATLAB scripts). To confirm that participants with low quality calibration data could be incorporated in the analysis, we plotted an aggregated heatmap of data from all trials and participants in that group (Figure S1).

For the main eye-tracking analysis, each infant viewed eight stimulus videos (each lasted for 16 s) in a unique pseudo-random order, interspersed with other videos (consisting of social stimuli, such as static and dynamic faces) not related to the current research question (Falck-Ytter et al., 2021). Incorporating unrelated social videos in non-social stimuli is a typical strategy to increase infants' attention to the screen in eye tracking experiments. The ANS videos consisted of a series of images, each of which showed two sets of dots, appearing on the left and right sides of the screen (Figure 1). Each image was unique in terms of a specific spatial constellation of dots.

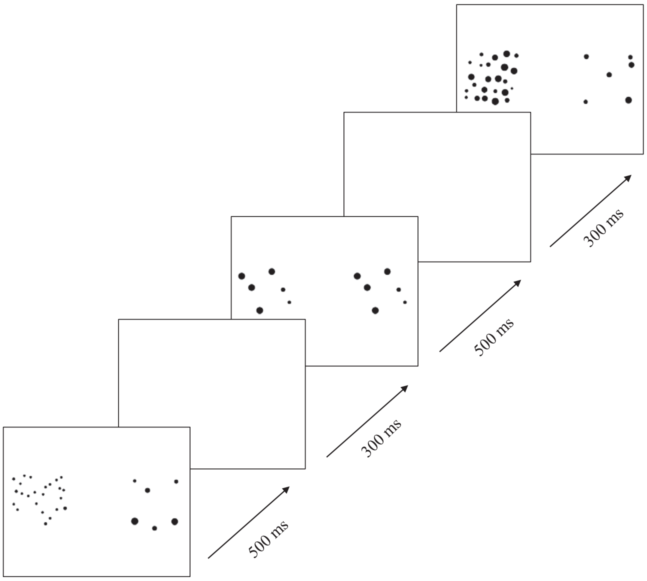

FIGURE 1 Experimental stimuli from the 1:4 ratio condition. Each image consisted of two sets of dots that was presented for 500 ms, followed by a blank screen for 300 ms. Every other image showed identical sets of dots on the right and left side the screen while remaining images differed in numerosity on the two sides

On one side of the screen, the collection of dots was numerically constant, while on the other side the collection of dots alternated in numerosity. The side with alternating numerosity switched between 10 and 20 dots (1:2 ratio condition) or six and 24 dots (1:4 ratio condition). The side with constant set sizes showed 10 dots and 6 dots, respectively, for these conditions. Libertus & Brannon (2010), which the task was adopted from, had both the smaller and larger set size as constant. In two experiments, they showed no effect of this manipulation (see Libertus & Brannon, 2010 Experiment 1 [p. 903] and Experiment 2 [p. 904]). Hence, we reasoned that this particular manipulation was not critical and opted for only the smaller set size as constant. Each condition consisted of four stimulus videos, which were counterbalanced in terms of left versus right location of the side with alternating set size. In half of the images where the two sets of dots differed in numerosity, the two sets of dots were matched on the total surface area. In the other half, the two sets of dots were matched on individual dot size. This was done in an effort to minimize the possibility to discriminate between the two images based on non-numerical cues (see Halberda et al., 2008 and Libertus & Brannon, 2010 for a similar approach). In 50% of the videos, the two sets of dots were controlled for convex hull (the smallest convex polygon that contains a set of dots). The main dependent variable in this study was the mean looking time at the numerically changing side (in relation to the whole screen), expressed as a percentage.

A trial was classified as invalid if the infant looked less than 20% of the time at the screen (~3.2 s), in order to allow the infants to observe the numerically changing dots. Infants were included in further analyses only if they had at least four valid trials (of which two from each condition, counterbalanced in terms of left vs right location of the numerically changing side). For the included infants, the number of invalid trials in the 1:4 ratio condition did not show a statistically significant association with age ($p = 0.812$), sex ($p = 0.167$), family income ($p = 0.444$), or parental education ($p = 0.991$).

The Mullen Scales of Early Learning (MSEL; Mullen et al., 1995) was also administered at the 5-month-visit. For almost all infants, the MSEL task was administered before the ANS task (although there were a few exceptions due to practical circumstances). MSEL is a standardized assessment commonly used in many areas of psychology as a measure of cognitive development. The MSEL consists of five subscales (gross motor, fine motor, visual reception, receptive language, and expressive language). Our pre-registered analysis plan specified the Early Learning Composite Score as the variable of interest, but this score did not meet three of the assumptions of twin modeling (the assumptions of equal variances within twins, equal means across zygosity, and equal variances across zygosity). We, therefore, combined the T-scores of the non-verbal scales (gross motor, fine motor, and visual reception) as a measure of non-verbal ability. For example, gross motor tasks include rolling over and sitting in a supported position, fine motor tasks include reaching for blocks and using pincher grasp, and visual reception tasks include tracking a moving bulls eye and looking for an object that drops on the floor. This combined variable fulfilled the assumptions of twin modelling, and the correlations among these three scales were all statistically significant ($r = 0.214$–0.361; $p < 0.01$). This measure of non-verbal ability was therefore used in all subsequent analyses.

2.3 | Statistical analyses

An analysis plan was pre-registered in OSF (https://osf.io/4h3gp/) after data collection and pre-processing but prior to statistical analysis. We used a univariate twin model to estimate the genetic and environmental contributions to the ANS score and non-verbal ability. The sources of variation in a trait can be divided into genetic influences (A; heritability), shared environment (C; environmental influences that make children growing up in the same family similar), and unique environment (E; environmental influences that make children growing up in the same family different; this also includes measurement error). Since monozygotic (MZ) twins share 100% of their segregating alleles, while dizygotic (DZ) twins on average share 50% of their segregating alleles, a higher similarity among MZ twins suggests a genetic contribution to a trait. Prior to running univariate twin models, we inspected the patterns of similarity across twins via intra-class correlations (ICCs). The 1:2 ratio condition showed a general but weak experimental effect (preference for the numerically changing side; see Table S1). The mean percentage of looking time at the numerically changing side (mean = 55.8%) was statistically different from 50% ($t = 10.98$, $p < 0.001$). However, unexpectedly we found that the MZ ICC was negative (−0.24; 95% CI: −0.41, −0.06; DZ ICC = 0.16; 95% CI: −0.05, 0.35), which is not predicted under any theoretical model. This unexpected finding precluded twin modeling based on this variable. It should be noted that while statistically different from 50% in our study with large sample size, it is very difficult for infants at this age to discriminate between numerosity at a 1:2 ratio (Libertus & Brannon, 2010; Xu et al., 2005). Presumably then, the weak experimental effect reflects chance factors in combination with near-random performance in this difficult condition. Against this background, and representing a change from our pre-registered plan, subsequent analyses used the 1:4 ratio condition only, which had a stronger experimental effect (Figure 2), and in which the ICCs were positive for both MZ and DZ.

Univariate models used the ANS 1:4 ratio condition score and the non-verbal MSEL score, with sex and age incorporated as covariates. The ANS variable was standardized before analysis. Data analysis was performed in R 3.6.3 (R Core Team, 2017), and model fitting was performed through maximum likelihood optimization with OpenMx, version 2.17.2 (Neale et al., 2016).

We also tested associations between ANS score and polygenic scores for ASD, ADHD, IQ and educational attainment. Details regarding these additional analyses are found in Supplementary Information S1.

3 | RESULTS

3.1 | Phenotypic specificity analyses

On average, the infants looked more at the numerically changing side than at the numerically constant side (see Table 1). There was no statistically significant association between mean looking time at screen and ANS (1:4 condition) score ($r = 0.06$, $p = 0.209$), suggesting that

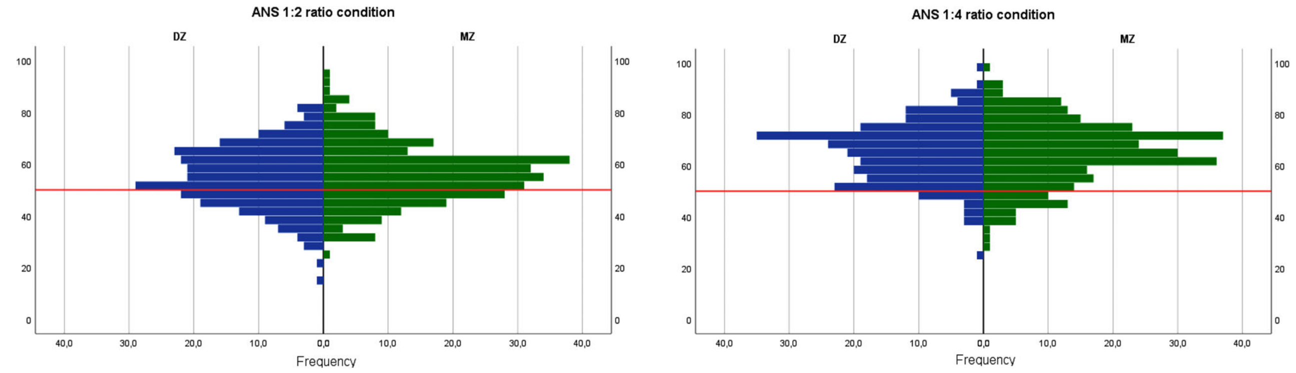

FIGURE 2 Distribution of the scores for MZ and DZ twins for the 1:2 ratio condition and the 1:4 ratio condition. The 50% level is marked with a red line, representing chance level, that is, no preference for the numerically changing side

TABLE 2 Cross-twin within-trait correlations

	ANS (1:4 ratio condition)	MSEL (non-verbal)
MZ	0.19 [0.01; 0.36]	0.42 [0.27; 0.54]
DZ	0.09 [−0.09; 0.27]	0.31 [0.14; 0.46]

Note: 95% confidence interval shown in brackets.

the ANS score does not merely reflect general attentional mechanisms. Given that we used shorter videos than earlier studies, we also examined the ANS score separately for the first and the second half of the trials. Notably, the mean ratio of looking at the numerically changing side was very similar in the first (0.63) and in the second (0.66) half of the 1:4 ratio trials, meaning that the ANS effect was present already in the first 8 s of the videos.

Secondly, we tested the association with non-verbal ability assessed with the MSEL. The phenotypic correlation between ANS score and the non-verbal MSEL score was close to zero ($r = -0.03$, $p = 0.535$). Since motor ability makes up the majority of our composite score, we tested the associations between ANS score and the separate scales included in the non-verbal MSEL score. We found no statistically significant association between ANS score and visual reception ($r = -0.03$, $p = 0.452$), gross motor ability ($r = -0.06$, $p = 0.160$), or fine motor ability ($r = 0.03$, $p = 0.517$). For completeness, we also explored the associations with the receptive and expressive language scales. There was no association with expressive language ($r = -0.075$, $p = 0.092$), but we found a statistically significant association between ANS score and receptive language ($r = -0.12$, $p = 0.009$; Supplementary Information S2).

3.2 | Twin analyses

The twin correlations for MZ and DZ twins for the ANS score and the non-verbal MSEL score suggested genetic influences on these measures (the MZ correlation being approximately twice as high as the DZ correlation; see Table 2). We, therefore, continued to fitting ACE models to the ANS and the non-verbal MSEL data.

First, fully saturated models were fitted to test the assumptions of equality of means and variances across zygosity and twin order (see Table S2). According to the saturated models, all assumptions were met for both variables. Next, ACE models were fitted for both variables, along with AE, CE, and E models for comparison (see Table 3).

For the ANS, the best fitting model was the AE model (based on the likelihood-ratio test and the AIC value), where the shared environment parameter was dropped. The AE model's estimates suggested significant modest heritability of the ANS (A = 0.18; 95% CI: 0.02, 0.33), with the majority of variance explained by unique environment, including measurement error (E = 0.82; 95% CI: 0.67, 0.98). The AE model was also the best fitting model for the non-verbal MSEL score, suggesting a moderate heritability (A = 0.47; 95% CI: 0.34, 0.57), with a moderate contribution of unique environment (E = 0.53; 95% CI: 0.43, 0.66). The non-verbal MSEL score used in the current study included gross motor ability, which is not typically included in cognitive measures for older children. However, performing the twin analysis without the gross motor score, and including only fine motor ability and visual reception, resulted in highly similar estimates (statistics not reported).

No statistically significant association was found between ANS score and polygenic scores for IQ ($\beta = 0.15$; $p = 0.786$) and educational attainment ($\beta = -0.00$; $p = 0.998$). Similarly, no statistically significant association was found between ANS score and polygenic scores for ASD ($\beta = 0.52$; $p = 0.427$) and ADHD ($\beta = 0.20$; $p = 0.756$).

4 | DISCUSSION

To our knowledge, this is the first twin study of individual differences in the ability to perceive approximate numerosity in infancy. The results indicate that variability in ANS acuity at 5 months of age to some extent reflect genetic factors. Further, the lack of positive association between ANS acuity and general cognitive ability indicates that these might be separate processes very early in life, despite showing a genetic overlap in adolescence (Lukowski et al., 2017). Indeed, when testing the different subscales of the MSEL separately, a negative association was observed. This pattern of results is in line with the idea that separate cognitive processes (with separate etiological influences)

TABLE 3 Model fitting

ANS (1:4 condition)											
Model	-2LL	# parameters	*df*	AIC	Comparison model	Δχ2	Δ df	*p*	A	C	E
Fully sat.	1445.72	12	502	441.72	-	-	-	-	–	–	–
ACE	1450.54	6	508	434.54	Fully sat.	4.83	6	0.57	0.18	0.01	0.82
AE	**1450.54**	**5**	**509**	**432.54**	**ACE**	**0.00**	**1**	**0.98**	**0.18**	**–**	**0.82**
CE	1450.98	5	509	432.98	ACE	0.44	1	0.51	–	0.14	0.86
E	1455.53	4	510	435.53	ACE	4.98	2	0.08	–	–	1.00
MSEL (non-verbal)											
Model	-2LL	# parameters	*df*	AIC	Comparison model	Δχ2	Δ df	*p*	A	C	E
Fully sat.	4634.74	12	551	3532.74	–	–	–	–	–	–	–
ACE	4645.31	6	557	3531.31	Fully sat.	10.56	6	0.103	0.34	0.11	0.55
AE	**4645.81**	**5**	**558**	**3529.81**	**ACE**	**0.50**	**1**	**0.479**	**0.47**	**–**	**0.53**
CE	4648.30	5	558	3532.30	ACE	3.00	1	0.083	–	0.36	0.64
E	4687.20	4	559	3569.20	ACE	41.89	2	<0.001	–	–	1.00

-2LL, fit statistic, the lower the better fitting is the model; df, degrees of freedom; AIC, an alternative fit index, lower value denotes better model fit; $\Delta\chi^2$, difference in −2LL statistic between two models, distributed χ^2; Δ df, difference in degrees of freedom between two models.

in infancy can become correlated over time (van der Maas et al., 2006), demonstrating the importance of genetically informed studies in early development.

The observed univariate heritability of the ANS is consistent with earlier twin studies in older samples (Lukowski et al., 2017; Tosto et al., 2014), which found a low-to-moderate contribution by genetic factors to individual differences in ANS acuity in late childhood and adolescence. In the current study, non-shared environment accounted for the majority of variance in ANS acuity, while shared environment did not seem to have any influence. The large non-shared environment component can in part reflect error measurement, but the clear experimental effect together with the observed heritability indicates that the task captures reliable group level differences and individual variation.

As noted, we found a weak but statistically significant association between ANS acuity and the receptive language scale of the MSEL. To our knowledge, negative correlations between abilities is rather rare in the literature, and we do not know of any theoretical explanation of this result. It is important to note that the language scale at this early age includes basic skills such as responding to social cues with positive affect, turning his/her head towards sounds, responds to simple gestural prompts etc. Although it is difficult presently to explain this result, it is notable that it clearly speaks against the view that better ANS acuity reflects more advanced language development. Although several studies indicate that infants can perceive relative numerosity (Libertus & Brannon, 2010; Wynn et al., 2002; Xu et al., 2005), few have examined the possible association between ANS acuity and other cognitive abilities at this age. Notably, we found no association between ANS acuity and the separate scales included in the non-verbal MSEL score (gross motor, fine motor, and visual reception). In contrast, Lukowski and colleagues (2017) found significant positive correlations between their ANS measure and general cognitive ability in two samples (8–16 years of age), but their measure of general cognitive ability primarily included tests of reading capacity, and their participants were older children and adolescents. Due to the young age of our sample, we believe that motor ability and visual reception were appropriate measures of general cognitive ability. In addition, we found no association between ANS acuity and mean looking time at the screen, suggesting that the ANS does not merely reflect a general attentional processes. A priority for future studies should be to measure the ANS and general cognitive ability at multiple time points, in order to distinguish the specificity of the ANS at different ages and thus its value for early mathematical ability.

We also found a moderate genetic influence on non-verbal ability in early infancy. Non-shared environment had a moderate contribution, while shared environment did not influence this ability. To the best of our knowledge, this is the first twin study of non-verbal ability in early infancy, although some studies have explored the genetic influence on this ability in older samples. For example, Price et al. (2000) measured non-verbal ability at 2 years and found that it was modestly influenced by genetic factors and that shared environment had a moderate-to-high influence. The difference in heritability estimates between their study and our current study might reflect the use of different age groups and different measures, and further research on the heritability of this measure at different time points is needed.

4.1 | Limitations

Due to unexpected twin correlations in the 1:2 ratio condition, we were unable to use this condition in subsequent analyses, creating a deviation from our pre-registered analysis plan. Presumably, this resulted from chance factors and the difficulty for infants at this age to discriminate between numerosity at a 1:2 ratio (Libertus & Brannon, 2010; Xu et al., 2005).

Currently, there are no large genom-wide association studies (GWASs) on mathematical ability. Therefore, we were not able to test the association between ANS score and polygenic scores for mathematical ability. While this study includes a large number of infant twins, we acknowledge that our sample is rather homogenous with regards to living area and SES. In order to discern the generalizability of our findings, the current study needs to be replicated in other samples.

5 | CONCLUSION

This study demonstrates a small-to-moderate genetic influence on ANS acuity in early infancy. It also indicates a lack of association between the ANS and concurrent cognitive skills such as non-verbal ability and general attention, suggesting that infants' sense of approximate numerosity is a heritable skill that is largely independent from other aspects of development.

AUTHOR CONTRIBUTIONS

The hypotheses and goals of this study were conceptualized by Marcus Lindskog, Charlotte Viktorsson, Angelica Ronald, and Terje Falck-Ytter. Data were analyzed by Charlotte Viktorsson, with support from Terje Falck-Ytter (eye tracking) and Mark J. Taylor (twin modelling). The experimental task was developed by Marcus Lindskog. Polygenic scores were calculated by Danyang Li and Kristiina Tammimies. Terje Falck-Ytter and Angelica Ronald were responsible for the overall BATSS project oversight and coordination. Charlotte Viktorsson and Terje Falck-Ytter drafted the manuscript, and all of the authors reviewed, edited, and approved the final manuscript for submission.

ACKNOWLEDGMENTS

The authors thank all participating families, as well as research assistants Linnea Hamrefors, Joy Hättestrand, Lynnea, Myers, Johanna Kronqvist, Sofia Jönsson, Anna Kernell, Carolin Schreiner, Sophie Lingö, Angelinn Liljebäck, Isabelle Enedahl, Matthis Andreasson, Lisa Belfrage, Mattias Savallampi, Isabelle Ocklind and Hjalmar Nobel Norrman. The genotyping was done at the SNP&SEQ Technology Platform, Uppsala University. This research was funded by the Swedish Research Council (grant number 2018–06232), Riksbankens Jubileumsfond in collaboration with the Swedish Collegium for Advanced Study (grant number NHS14-1802:1), Knut and Alice Wallenberg Foundation, and HORIZON EUROPE Marie Sklodowska-Curie Actions (grant number MSCA-ITN-2018N.81). The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

CONFLICT OF INTEREST

All authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

This study was preregistered (http://osf.io/4h3gp/). Deviations from the preregistration are discussed in the text. Custom-made scripts for pre-processing and statistical analyses will be made available upon reasonable request to corresponding author. Note that sharing of pseudonymized personal data will require a data sharing agreement, according to Swedish and EU law.

ETHICS STATEMENT

The study was approved by the regional ethics board in Stockholm and was conducted in accordance with the Declaration of Helsinki.

ORCID

Charlotte Viktorsson https://orcid.org/0000-0003-2727-2957
Marcus Lindskog https://orcid.org/0000-0003-1326-6177

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Viktorsson, C., Lindskog, M., Li, D., Tammimies, K., Taylor, M. J., Ronald, A., & Falck-Ytter, T. (2022). Infants' sense of approximate numerosity: heritability and link to other concurrent traits. *Developmental Science*, 00, e13347. https://doi.org/10.1111/desc.13347