Space modulates cross-domain transfer of abstract rules in infants

Hermann Bulf[1,2], Chiara Capparini[3], Elena Nava[1,2], Maria Dolores de Hevia[4,5], & Viola Macchi Cassia[1,2]

[1] Department of Psychology, University of Milano-Bicocca, 20126 Milano, Italy

[2] Milan Center for Neuroscience (NeuroMI), 20126 Milano, Italy

[3] Department of Psychology, Lancaster University, Lancaster LA1 4YW, UK

[4] Sorbonne Paris Cité - Université Paris Descartes, 75006 Paris, France

[5] Integrated Neuroscience and Cognition Center (INCC), CNRS, UMR 8002, 75006 Paris, France

(for the last author, Macchi Cassia is the double family name)

Corresponding author: Hermann Bulf, Department of Psychology, University of Milano-Bicocca, 20126 Milano, Italy; e-mail: hermann.bulf@unimib.it

Abstract

Developmental studies have shown that infants exploit ordinal information to extract and generalize repetition-based rules from a sequence of items. Within the visual modality, this ability is constrained by the spatial layout within which items are delivered, as a left-to-right orientation boosts infants' rule learning (RL), whereas a right-to-left orientation hinders this ability. Infants' RL operates across different domains and can also be transferred across modalities when learning is triggered by speech. However, no studies have investigated whether the transfer of rule learning occurs across different domains when language is not involved. Using a visual habituation procedure within a visual RL task, we tested 7-month-old infants' ability to extract rule-like patterns from numerical sequences and generalize them to non-numerical sequences of visual shapes, and whether this ability is affected by the spatial orientation of the sequences. Infants were first habituated to left-to-right or right-to-left oriented numerical sequences instantiating an ABB rule, and were then tested with the familiar rule instantiated across sequences of single geometrical shapes and a novel (ABA) rule. Results showed a transfer of learning from number to visual shapes for left-to-right oriented sequences, but not for right-to-left oriented ones (Experiment 1), even when the direction of the numerical change (increasing vs. decreasing) within the habituation sequences violated a small-left/large-right number-space association (Experiment 2). These results provide the first demonstration that visual rule learning mechanisms in infancy operate at a high level of abstraction and confirm earlier findings that left-to-right oriented directional cues facilitate infants' representation of order.

Introduction

The ability to process, memorize, and retrieve the ordinal position of an element within an ordered sequence is a fundamental aspect of cognition, and has important adaptive meaning. Indeed, many of our daily activities – ranging from language to goal-directed actions and social routines – are sequentially organized (Baldwin & Baird, 2001; Lashley, 1951). Developmental studies have shown that preverbal infants are capable of parsing the ordinal structure of event sequences (e.g., Lewkowicz, 2004, 2013) and of using ordinal information to discriminate numerical and non-numerical magnitude relations (Macchi Cassia, de Hevia, Picozzi, & Girelli, 2012; Picozzi, de Hevia, Girelli, & Macchi Cassia, 2010; Suanda, Tompson, & Brannon, 2008).

Infants can capitalize on ordinal information also to implicitly learn high-order rule-like structures defined by the presence of item repetitions and their ordinal position within visual sequences. This mechanism, known as rule learning, was first investigated in infants by Marcus and colleagues (1999), who showed that 7-month-old infants were able to extract repetition-based rules (i.e., ABB, AAB, ABA) within 3-item sequences of syllables, and to generalize them to novel syllables. Inspired by this seminal paper, several studies have followed, showing that rule learning skills in infancy are not confined to the linguistic domain. For example, infants are able to learn abstract rules from sequences of auditory non-linguistic stimuli (Ferguson & Lew-Williams, 2016; Marcus, Fernandes, & Johnson, 2007), geometrical shapes (Bulf, de Hevia, Gariboldi, & Macchi Cassia, 2017; Johnson et al., 2009), faces (Bulf, Brenna, Valenza, Johnson, & Turati, 2015), and patterns of touch (Lew-Williams, Ferguson, Aby-Zhaya, & Seidl, 2019). Together, this evidence has led researchers to conclude that rule learning is a domain-general mechanism (e.g., Rabagliati, Ferguson, Lew-Williams, 2019; for the debate on the domain-specificity vs. domain-generality of serial order processing see Endress, 2009). Of note, infants' generalization of the learned rule implies the ability to go beyond the surface features of the stimuli by representing the high-order rule-like structure at an abstract level.

The idea that infants can create abstract representations when they learn repetition-based rules is confirmed by evidence showing that infants can transfer rules from sequences of speech sounds to sequences of musical tones, timbres, and animal sounds (Marcus, Fernandes, & Johnson, 2007). This evidence demonstrates that infants' rule learning skills are not confined to specific stimulus materials, and that the rule-like structures that infants extract and represent are abstract enough to be transferred and recognized across different stimulus domains within the auditory modality (from linguistic to non-linguistic stimuli). Importantly, it has been recently shown that rules can also be transferred across modalities when learning is triggered by speech sounds.

Although infants are equally able to learn rules from streams of linguistic sounds (Marcus et al., 1999) and visual shapes (Bulf et al., 2005), it has been showed that they can generalize ABB and ABA rule-like patterns delivered by speech sounds to visual triplets, but fail to transfer learning from shapes to speech (Bulf et al., 2021). These results suggest that language plays a critical role in infants' abstraction and generalization of high-order rules, as transfer of learning across domains occurs only when a given rule is acquired from linguistic stimuli. Nonetheless, no attempts have been made so far to test whether transfer of learning occurs across different domains when language is not involved. Addressing this question would be particularly relevant to understand how abstract the representation of the learned rule is, and how truly domain-general infants' rule learning skills are.

Accordingly, in the current study we investigated whether 7-month-old infants are able to extract rule-like patterns from numerical sequences and generalize them to non-numerical sequences of visual shapes. Prior studies have shown that, at least by 4 months of age (de Hevia et al., 2017), infants succeed at detecting magnitude differences within sets of non-symbolic numbers and at representing the ordinal structure (i.e., increasing or decreasing) emerging from those differences. After habituation to increasing or decreasing numerical sequences, they generalize habituation at test to new numerical displays arranged in the familiar order while they dishabituate to the same displays arranged in a novel order (Picozzi, de Hevia, Girelli, & Macchi Cassia, 2010; Suanda, Tompson, & Brannon, 2008). In the current study, we investigated whether infants can extract the ABB rule-like structure when it is instantiated over numerosities and transfer it to a different non-numerical context.

A second goal of the current study was to test whether infants' ability to transfer the learning of a high-order rule between different visual domains is constrained by the spatial layout within which the visual sequences are delivered. Indeed, prior studies have shown that, when spatial information is introduced in the numerical ordinal task described above, 7-month-old infants show a preference for increasing, left-to-right oriented, numerical sequences (de Hevia et al., 2014, Exp. 3), and fail to discriminate order information when numerical sets appear along a right-to-left orientation (de Hevia et al., 2014, Exps. 1 and 2). These findings were taken as evidence that, well before the acquisition of symbolic knowledge and language, infants associate numerical order to an oriented spatial continuum, which might lie at the root of oriented mental number line (Dehaene, 1992) observed in adult cognition (see also Macchi Cassia, Bulf, McCrink, & de Hevia, 2017, and Macchi Cassia, McCrink, de Hevia, & Bulf, 2016 for other, more indirect, evidence of a spatial representation of numerical and size-based ordered series in infants).

However, recent evidence suggests that, like in adulthood (see review in Abrahamse, Van

Dijck, & Fias, 2017), in infancy the mapping of increasing numerical order into left-to-right oriented spatial codes is an instance of a more general strategy of representing order information along a spatial continuum, which, at least in Western cultures, is oriented from left to right. Indeed, Bulf and colleagues (Bulf, de Hevia, Gariboldi, & Macchi Cassia, 2017) have shown that spatial information has a critical impact on infants' learning of rule-like structures from visual sequences. Italian, 7-month-old infants succeeded at generalizing the rule specified by adjacent-late (ABB) or non-adjacent (ABA) repetitions within 3-item sequences of visual shapes to novel shapes when the sequences appeared from left to right. On the contrary, they failed at the same task when the sequences had a right-to-left orientation. These findings were interpreted as indicating that the linking of each item to distinct adjacent positions along a left-to-right spatial continuum helped infants to extract serial order information defining the high-order structures, thus boosting their rule learning abilities. Accordingly, when presented with left-to-right oriented sequences, 7-month-olds succeeded in learning and generalizing not only the ABB rule, which involves adjacent repetitions of the B element, but even the more complex ABA rule, which involves non-adjacent repetitions of the A element, and is typically not discriminated at this same age in the absence of spatial information (i.e., when visual sequences are presented centrally on the screen; Johnson et al., 2009). These findings led the authors to conclude that infants' processing of serial order information is enhanced when the spatial layout within which the information is provided is congruent with the dominant direction of their cultural environment.

Based on this evidence, in the current study we manipulated the spatial orientation of the sequences delivering the rule. More specifically, we habituated infants with left-to-right or right-to-left oriented numerical sequences instantiating an adjacent repetition-based (ABB) rule and tested their ability to generalize the learnt rule to sequences of geometric shapes whose spatial orientation matched the orientation seen during habituation. In two different studies, we also manipulated the direction of numerical change (i.e., increasing vs. decreasing) between the items of the habituation sequences so that numerical order within the sequences was either congruent (Exp. 1) or incongruent (Exp. 2) with the preferred left-to-right orientation of increasing order. We reasoned that, if a left-to-right spatial layout boosts infants' ability to extract ordinal information from visual sequences and a right-to-left spatial layout hinders such ability, infants should learn and generalize the abstract ABB rule-like structure from left-to-right oriented numerical sequences, and should fail with right-to-left oriented sequences, irrespective of the direction of the numerical change within the sequences.

As the surface features of the numerical arrays varied systematically and the repetitions delivering the rule within each numerical sequence were instantiated by perceptually different

5

arrays, infants' learning of the rule could only rely on abstract numerosity, not on item perceptual features. Moreover, to succeed in transferring the repetition-based structure extracted from a numerosity-based context to the shape-based scenario, infants could only rely on an abstract representation of the rule. Therefore, our rule learning task involved both the extraction and representation of some abstract features of the input (i.e., same-different relations and numerosity), and the cross-domain generalization of those features.

Experiment 1

In Experiment 1, two groups of infants were habituated to either left-to-right or right-to-left oriented numerical sequences instantiating the ABB rule, in which numerosity changed from the first to the second display and remained unchanged from the second to the third display. For both orientations, the direction of the numerical change between the A and B elements was congruent with a left-small/right-large representation of numerical magnitude, with smaller numbers on the left, and larger numbers on the right. Indeed, the numerical change matched a left-small/right-large association, as numerosities changed from smaller to larger (i.e., 6-12-12, 9-18-18, 12-24-24) within the left-to-right oriented sequences, and from larger to smaller (i.e., 12-6-6, 18-9-9, 24-12-12) within the right-to-left oriented sequences. Therefore, all habituation sequences matched a left-small/right-large association and were all an instantiation of the same ABB rule, the only difference being the specific spatial orientation along which the numerical displays were presented. Habituation trials were followed by six test trials in which both the familiar (ABB) and a novel (ABA) rule in alternation were instantiated by sequences of geometrical shapes presented with the same left-to-right or right-to-left spatial orientation shown during the habituation phase.

Following earlier demonstrations of rule learning generalization from speech to non-speech sounds (Marcus et al., 2007) and from speech to visual shapes (Bulf et al., 2021) we expected that, provided that they extracted the ABB rule based on abstract numerosities, infants would be able to transfer the rule to shape-based sequences. Moreover, following earlier demonstrations of a learning advantage for left-to-right oriented rule-based sequences (Bulf et al., 2017) and for left-to-right oriented numerosities (de Hevia et al., 2014), we expected to observe longer looking times to the novel rule at test for infants presented with left-to-right oriented sequences but not for those presented with right-to-left oriented sequences.

Method

6

Participants

Fifty-two healthy, full-term Caucasian infants were recruited to take part in the experiment. Four infants were excluded from the final sample because of fussiness (N = 2), technical problems (N= 1), or due to looking times < 1 s (N = 1). Thus, the final sample included 48 seven-month-old infants (19 females; mean age = 7 months, 15 days; range = 6 months, 12 days to 8 months, 6 days). A Power Analysis performed using G*Power (Faul & Erdfelder, 1992) for a 2 measurements x 2 groups design revealed that at least 44 participants were required to obtain a Power of .90 considering an alpha level of .05 and a medium effect size (0.25). Participants were recruited via a written invitation sent to their parents based on birth records provided by neighboring cities. The procedure was approved by the ethical committee of the University of Milano-Bicocca. Parents gave written informed consent for their infants' participation.

Stimuli and procedure

Habituation stimuli were 36 numerical arrays containing colored rectangular-shaped items arranged randomly on a 16° x 10.5° white area that appeared on a black background. Stimuli were generated using E-Prime 1.0 software. The numerical arrays were organized into three stimulus pairs (6-12; 9-18; 12-24), each displaying the same numerical distance (1:2), and presented in a different color ('blue' for the 6-12 set, 'red' for the 9-18 set, 'green' for the 12-24 set) (Figure 1).
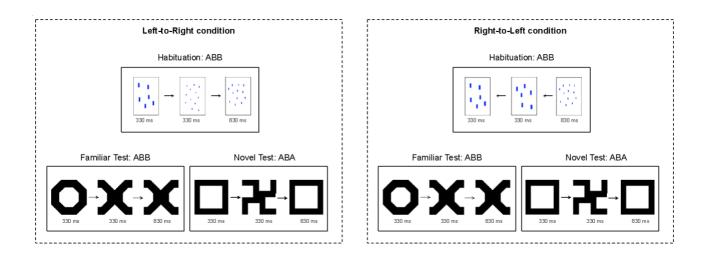

Figure 1: Examples of the habituation sequences (numerical arrays) and test sequences (geometrical shapes) presented to infants in the Left-to-Right and the Right-to-Left conditions of Experiment 1.

Numerical arrays within each pair came in six different exemplars differing in overall

surface area, contour length, density and spatial arrangement of the rectangular shaped items, and these different exemplars were randomly combined by the E-Prime software to generate ABB triplets in which the first item was always smaller than the second item, which was repeated twice (e.g., 6-12-12). Since the numerical arrays composing the triplets were selected randomly, continuous dimensions did not consistently co-vary with number, therefore they were not informative of the increasing or decreasing numerical change between the A and the B element within each sequence. Moreover, since the repetitions of the B element were instantiated by two, perceptually different arrays, item surface features were not informative of the presence of the ABB rule. Test stimuli consisted of four black geometrical shapes (Figure 1) embedded in a 10° x 10° virtual area. Four unique shapes were assigned to the A group and four to the B group; the A and B images were randomly combined by the software to generate 4 different ABA triplets and 4 different ABB triplets. Stimuli were sequentially presented either from left to right or from right to left, with the same spatial directionality across both the habituation and the test sequences. For the left-to-right sequences, the first stimulus was displayed on the left side of the monitor for 330 ms, the second stimulus was displayed in the middle of the monitor for 330 ms, then the third stimulus was displayed on the right side of the monitor for 830 ms. For the right-to-left sequences, the stimuli were presented from right to left. The distance between the center of each stimulus was about 15° of visual angle. A blank screen (500 ms) separated the triad presentations on each trial. Half of the infants were randomly assigned the left-to-right condition, the other half to the right-to-left condition.

As infants were presented with colored numerical arrays during the habituation phase and with black geometrical shapes during the test phase, a general novelty response at the test trials due to the introduction of stimuli with new colors and sizes would be expected. To avoid this issue, prior to the habituation trials, infants were familiarized with both the ABB and ABA (test) triplets. Infants were administered two familiarization trials, on each trial one of the two test triplets remained visible until the infant had looked for 20 s. An animated image associated with varying sounds served as attention getter before each familiarization, habituation and test trial began. As soon as the infant fixated the screen the experimenter initiated the trial, and recorded the infant's fixation by holding the mouse button whenever the infant fixated on the stimulus. Habituation and test trials continued until the infant looked continuously for a minimum of 500 ms and ended when the infant looked away for 2 consecutive seconds or looked for a maximum of 60 s. Each habituation trial consisted of triads of numerical arrays, randomly selected from the three stimulus pairs (i.e., 6-12; 9-18; 12-24), organized in the ABB pattern (e.g., 6-12-12). Habituation trials continued until the infant either saw a maximum of 25 trials (after Bulf et al., 2017) or met the

habituation criterion, which was defined as a 50% decline in looking time on three consecutive trials, relative to the looking time on the first three trials (Slater, Morison, & Rose, 1984). Following the habituation phase, infants were given 4 test trials in which ABA (novel) and ABB (familiar) triplets, composed of geometrical shapes, were presented alternately, each for two times. Order of presentation (i.e., novel or familiar first) was counterbalanced across infants. Looking time (s) towards novel and familiar triplets was recorded as the dependent variable.

Apparatus

Each infant was tested while sitting on an infant seat or on the parent's lap approximately 60 cm from a 24" screen (1920 x 1200-pixel resolution) where the stimuli were presented. Parents were instructed to refrain from interacting with their infants and to close their eyes during the test sequences. The infant's eyes were recorded through a video-camera hidden above the screen, which fed into a TV monitor and a digital video recorder, both located outside the testing cabin. The live image of the infant's face was displayed on the TV monitor to allow the online coding of the infant's looking times through the E-Prime program by the experimenter, who was blind to the condition the infant was assigned. The image of the infant's face was also recorded via a Mini-DV digital recorder for a frame-by-frame offline coding of looking times during test trials. About 33% of the infants' (N = 14) looking times were coded offline by a second independent observer who was blind to the experimental condition. Inter-observer agreement (Pearson correlation) between the two observers (i.e., the one who coded the data online and the one who coded the data from digital recordings), as computed on total fixation times during test trials, was $r = .99$, $p < .001$.

Results and discussion

All infants reached the habituation criterion. Neither total habituation time, $M = 73.14$ s (*SE* = 8.75) vs. $M = 81.03$ s (*SE* = 14.81), $t(46) = 0.66$, $p = .65$, nor number of trials to habituate, $M = 8.46$ trials (*SE* = 0.62) vs. $M = 10.96$ (*SE* = 0.62), $t(46) = 1.72$, $p = .09$, differed for infants tested in the left-to-right vs. right-to-left conditions.

To determine whether infants' discrimination between the familiar from the novel rule-like patterns was affected by the spatial orientation of visual sequences , a repeated-measures ANOVA was performed on looking times during test trials, with spatial orientation (left-to-right vs. right-to-left) and test trial order (familiar first vs. novel first) as between-participants factors, and test trial pair (first vs. second) and test trial type (novel vs. familiar) as within-participants factors. The analysis revealed a main effect of test trial pair, $F(1,44) = 14.36$, $p < .001$, $\eta^2 = .25$, as infants looked longer to the first pair of test trials ($M = 11.44$ s, *SE* = 1.33) than to the second ($M = 7.49$ s,

SE = .67), indicating an overall decay of attention during the last test trials. Moreover, there was also a Test Trial Type x Spatial Orientation interaction, $F(1,44) = 5.58$, $p = .023$, $\eta^2 = .11$. Planned comparisons confirmed that looking times to the novel test trials were significantly longer than those to the familiar trials for infants tested in the left-to-right condition (novel: *M* = 12.95 s, *SE* = 2.14 vs. familiar: *M* = 9.59 s, *SE* = 1.3; $p = .024$), but not for infants tested in the right-to-left condition (novel: *M* = 7.22 s, *SE* = .82 vs. familiar: *M* = 8.1 s, *SE* = 1.41, $p = .44$) (Figure 2). No other main effect nor interaction were significant (all $ps > .17$).

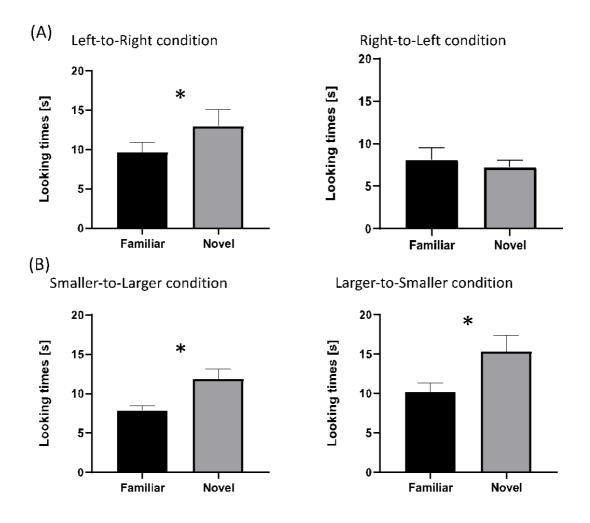**Figure 2: Mean looking times (±SE) to familiar and novel test trials for infants tested in the Left-to-Right and Right-to-Left conditions of Experiment 1 (A), and for infants tested in the Smaller-to-Larger and Larger-to-Smaller conditions of Experiment 2 (B). *$p < 0.05$.**

Results indicated that infants tested in the left-to-right condition were able to extract the ABB rule-like structure from the numerical sequences showed during habituation and to generalize it to a sequence of geometrical shapes in the test phase, providing evidence that infants' rule

10

learning can operate at a truly abstract level. Crucially, the transfer of learning across visual domains was modulated by the spatiotemporal layout within which the visual sequences were delivered to the infants, as only when the stimuli were presented from left to right infants showed evidence of discriminating between the familiar ABB rule and the novel ABA rule. The absence of significant discrimination at test for infants presented with right-to-left oriented sequences suggests that infants either failed to learn and abstract the ABB rule-like structure embedded in the numerical sequences during habituation, or that they failed to recognize the familiarity of the ABB rule instantiated by the non-numerical visual shapes composing the test triplets.

Overall, the results of Experiment 1 are in line with those from earlier studies showing a left-to-right spatial bias in infants' sequential learning of increasing/decreasing numerical sequences (de Hevia et al., 2014) and non-numerical rule-based sequences (Bulf et al., 2017). However, in light of earlier demonstrations of a learning advantage for increasing over decreasing left-to-right oriented numerical order (de Hevia et al., 2017), we cannot exclude that the observed asymmetry in infants' ability to extract rules from the numerical habituation sequences in the current study was due to the specific coupling between the direction (i.e. increasing) of the numerical change (i.e. increasing) and the spatial orientation (i.e., left-to-right) along which the numerical displays were presented. Experiment 2 aimed to test this possibility by investigating whether the ability to learn the ABB rule-like structure from left-to-right oriented numerical sequences, and to generalize it to non-numerical sequences at test, is maintained when the direction of numerical change instantiating the rule does not match a small-left/large-right spatial association.

Experiment 2

In Experiment 2, two groups of infants were habituated to left-to-right oriented increasing vs. decreasing numerical sequences instantiating an ABB rule (Figure 3). Increasing numerical sequences, in which numerosities changed from smaller to larger (i.e., 6-12-12, 9-18-18, 12-24-24), were congruent with a left-small and right-large number-space association, while decreasing numerical sequences violated such association, as numerosities changed from larger to smaller (i.e., 12-6-6, 18-9-9, 24-12-12). Infants' learning of the ABB rule was inferred from looking times to the familiar and novel rule instantiated by geometrical shapes at test. The comparison between infants' performance in the increasing vs. decreasing condition allowed us to determine whether the reported learning advantage for increasing over decreasing numerical order (de Hevia et al., 2017) had an impact on infants' ability to represent abstract rules.

11

<center>**Method**</center>

Participants

The final sample included 48 seven-month-old infants (23 females; mean age = 7 months, 18 days; range = 6 months, 27 days to 8 months, 3 days). Five more infants were tested but excluded from the sample because of fussiness. Participants were recruited via a written invitation sent to parents based on birth records provided by neighboring cities. The procedure was approved by the ethical committee of the University of Milano-Bicocca. Parents gave their written informed consent for their infants' participation.

Stimuli, apparatus and procedure

Habituation and test stimuli were the same as those presented in the left-to-right condition of Experiment 1. In the increasing condition, numerosities changed from smaller to larger (i.e., 6-12-12; 9-18-18; 12-24-24), while in the decreasing condition they changed from larger to smaller (i.e., 12-6-6; 18-9-9; 24-12-12). The apparatus and procedure were the same as in Experiment 1. Inter-observer agreement (Pearson correlation) between the two observers who coded the data live and from digital recordings, as computed on total fixation times during test trials for about 33% of infants (N = 14), was $r = .98$, $p < .001$.
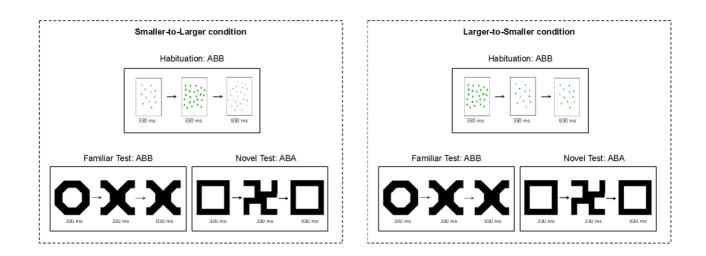

Figure 3: Examples of the habituation sequences (numerical arrays) and test sequences (geometrical shapes) presented to infants in the Smaller-to-Larger and the Larger-to-Smaller conditions of Experiment 2.

<center>12</center>

Results and discussion

All infants reached the habituation criterion. No differences were observed in total habituation time, $M = 94.26$ s ($SE = 6.68$) vs. $M = 118.19$ s ($SE = 10.99$), t(46) = 1.86, p = .07, and number of trials to habituate, $M = 10.21$ ($SE = 0.85$) vs. $M = 8.92$ ($SE = 1.02$), $t(46) = 0.97$, $p = .34$, between the increasing vs. decreasing condition.

To compare infants' total looking times toward the novel and familiar test sequences, we ran a 4-way ANOVA with direction of numerical order (increasing vs. decreasing) and test trial order (familiar first vs. novel first) as between-participants factors, and test trial pair (first vs. second) and test trial type (novel vs. familiar) as within-participants factors. In addition to a significant Test trial pair main effect, $F(1,44) = 9.07$, $p = .044$, $\eta^2 = .17$, the analysis revealed a main effect of test trial type, $F(1,44) = 21.95$, $p < .001$, $\eta^2 = .33$, indicating that infants looked generally longer to the novel test sequences ($M = 13.56$ s, $SE = 1.15$) than to the familiar ones ($M = 8.99$ s, $SE = .65$), irrespective of the direction (increasing vs. decreasing) of the numerical change embedded within the left-to-right oriented habituation sequences.

Results showed that the increasing versus decreasing direction of numerical change within the sequences did not impact infants' ability to build an abstract representation of the ABB rule that could be successfully generalized to the rule-based sequences of visual shapes at test. Indeed, infants' transfer of rule learning from numbers to non-numerical visual sequences was always possible under left-to-right spatiotemporally organized presentation, irrespective of the nature of the numerical information instantiating the learnt rule.

General discussion

In the current study, we investigated infants' ability to transfer abstract rules between visual domains by testing their ability to learn ABB relations from spatially oriented sequences of numerical displays and generalize them to sequences of non-numerical visual shapes. To succeed in the task, infants had to create an abstract representation of the ABB rule. Indeed, numerical displays within each sequence differed in shape, size, color, density and spatial arrangement of the rectangular-shaped elements, so that abstract numerosity was the only available cue to detect repetition-based structures. Moreover, there was no overlap of any kind between surface features of the habituation and the test sequences, so that recognition of the ABB rule-like structure could only rely on cross-domain generalization of the rule.

Overall, our results indicate that infants were able to transfer a rule from number to visual shapes, and that this ability was impacted by the spatial orientation in which the numerical and non-numerical sequences were provided. In Experiment 1, two groups of infants were shown rule-based numerical sequences appearing along a left-to-right orientation or a right-to left orientation, and only infants in the former group showed significant differences in looking times between sequences of visual shapes instantiating the familiar and the novel rules. This finding extends earlier demonstrations that directional spatial cues modulate infants' rule learning from sequences of visual shapes (Bulf et al., 2017), and provides the first evidence that visual rule learning mechanisms in infancy operate at a high level of abstraction.

The current demonstration that infants were able to learn the ABB rule from numerical sequences based on the detection of (late) repetition of purely numerical information in the face of changeable perceptual features is the first to extend previous evidence obtained with linguistic stimuli to the visual perceptual domain. Indeed, Kovács (2014) has shown that 7-month-old infants could extract the AAB pattern from streams of syllables where adjacent repetitions were based on phonological identity (i.e., the same syllable) in the presence of physical variability (i.e., different pitch). Here, continuous dimensions did not consistently co-vary with number since overall surface area, contour length, density and spatial arrangement of the rectangular shaped items all varied randomly across numerical arrays. Thus, infants could only rely on numerical information to extract the ABB rule, as perceptual features were not informative neither of the increasing or decreasing numerical change between the A and the B element within each sequence, nor of the numerical equality across the repetitions of the B element.

Infants' ability to extract the ABB pattern from variable visual stimuli based on purely numerical identity, along with their successful generalization of the repetition-based pattern to novel non-numerical stimuli, suggests that, at least in the case of adjacent identity relations, infants' visual rule learning involves computations that operate at a high level of abstraction. A question that remains open to further investigation is whether infants' abstraction of the rule and its cross-domain generalization involve the redescription of the repetition-based structure into a unitary mental representation that is available in itself for further computations, or whether it more simply reflects the representation of the abstract features of the sequences defining the rule (i.e., repetitions and their ordinal position in the sequence) (see discussion in Kabdebon & Dehaene-Lambertz, 2019). Moreover, since in the present study infants were habituated to ABB triplets where the to-be-learned rule involved an adjacent item repetition, further studies should further investigate whether the transfer of learning across visual domains generalizes to abstract structures specified by non-adjacent identity relations, as in the case of ABA rules.

A related goal of the current study was to investigate whether spatial orientation –left-to-right vs. right-to-left– and the direction of numerical change between sequence items –i.e., increasing vs. decreasing– interacted in modulating infants' learning of rule-like structures. Our results showed that this was not the case: infants' generalization of the ABB pattern was hindered when the spatial layout of the visual sequences was right-to-left oriented, while it manifested easily when the sequences were presented from left to right (Exp. 1), irrespective of the increasing or decreasing directions of the numerical changes instantiating the rule (Exp. 2). This finding replicates earlier demonstration that, at 7 months, infants' learning of numerical order is hindered for right-to-left oriented numerical sequences irrespective of the direction of numerical change within the sequences (de Hevia et al., 2014).

To date, evidence of rule learning generalization in the absence of spatial information (i.e., when visual sequences are presented centrally on the screen) is missing. Therefore, we cannot conclude whether the left-to-right oriented deployment of the numerical items was critical in allowing infants to build a representation of the adjacent identity relations which could be generalized to a new context. Alternatively, it could also be the case that the right-to-left spatial layout of the sequences disrupted infants' ability to extract structure from a numeric learning context and/or generalize it to a new context. Future studies with centrally presented sequences of visual stimuli shall prove critical in answering this question. Moreover, it has been recently claimed that passive exposure to directionally-relevant culturally-driven routines may play a relevant role in shaping the directionality of the order-space mapping from the earliest stages of development (e.g., Göbel, McCrink, Fischer, Shaki, 2017; Patro, Nuerk, Cress, 2016). In light of this, future studies may investigate the role of spatial orientation in modulating transfer of abstract rule learning by testing infants growing up in cultures with different dominant reading-writing directions, which provide infants with different directionally-relevant experiences (e.g., see Macchi Cassia et al., 2020 for evidence from a cross-cultural visual RL study with infants).

In sum, the present study provides the first evidence that infants can transfer learning of abstract rules across different visual domains. These findings extend previous demonstrations of abstract rule learning (Kovács, 2014), and learning transfer triggered by linguistic stimuli (Bulf et al., 2021; Marcus et al., 2007), and document, for the first time, that infants' rule learning in the visual domain operates at a high level of abstraction. The current results also replicate and extend previous demonstrations of a spatial bias in 7-month-old infants' ability to extract structure from visual sequences (Bulf et al., 2017; de Hevia et al., 2014), and extend it to a more demanding condition, where the learned structure had to be generalized across contexts.

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