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RESEARCH ARTICLE

Rule learning transfer across linguistic and visual modalities in 7-month-old infants

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Abstract

Rule learning (RL) refers to infants' ability to extract high-order, repetition-based rules from a sequence of elements and to generalize them to new items. RL has been demonstrated in both the auditory and the visual modality, but no studies have investigated infants' transfer of learning across these two modalities, a process that is fundamental for the development of many complex cognitive skills. Using a visual habituation procedure within a cross-modal RL task, we tested 7-month-old infants' transfer of learning both from speech to vision (auditory-visual—AV—condition) and from vision to speech (visual-auditory—VA—condition). Results showed a transfer of learning in the AV condition, but only for those infants who were able to efficiently extract the rule during the learning (habituation) phase. In contrast, in the VA condition infants provided no evidence of RL. Overall, this study indicates that 7-month-old infants can transfers high-order rules across modalities with an advantage for transferring from speech to vision, and that this ability is constrained by infants' individual differences in the way they process the to-be-learned rules.

KEYWORDS
abstraction, rule learning, transfer, cross modal, infants

1 | INTRODUCTION

The ability to extract structure from a given learning context and to generalize it to new contexts is a basic hallmark of human cognition. Transfer of learning across contexts requires abstraction and it is fundamental for the development of many complex cognitive skills, from language (Pinker, 1991) to the understanding of goal-directed actions (Baldwin & Baird, 2001) and social interactions (Woodward, 2009).

Research on infants' rule learning (RL) indicates that the ability to generalize abstract structure to new instances is present early in life. RL refers to the ability to extract repetition-based rules (ABB/AAB/ABA) from a sequence of elements and to generalize them to new items (Marcus et al., 1999). Infants' RL was first demonstrated for speech sequences (Marcus et al., 1999): after being familiarized for 2 min to a sequence of syllables that followed a repetition-based rule, 7-month-olds were able to generalize the rule to a novel set of syllables, providing evidence that they extracted and generalized the items' structure beyond the perceptual dimension of the stimuli. Infants' RL has recently been demonstrated in the visual modality as well, most robustly in the presence of highly experienced stimuli (faces: Bulf et al., 2015; images of familiar animals: Saffran et al., 2007). When exposed to sequences of visually low-experienced stimuli (unfamiliar shapes), 7-month-old infants succeeded in extracting the embedded rules only when the stimuli were presented from left-to-right (Bulf et al., 2017), while they failed with a right-to-left presentation. When no spatial information was provided (i.e., when the sequences were presented centrally on the screen), they were only capable to detect and represent rules defined by the adjacent repetition of one item (ABB), but not those defined by non-adjacent item repetition (ABA; Johnson, 2009). RL is not specific to human species, as it has been observed in nonhuman animals as well, with both speech (monkeys: Hauser et al., 2002; rats: de La Mora & Toro, 2013) and visual items (chicks: Santolin et al., 2016). These findings indicate that both human infants and non-human animals are able to use abstract knowledge when faced with a learning context that involves new stimuli, and suggest that a form of abstraction (i.e., generalization of repetition-based rules) is shared among species.

Infants are able to generalize a rule not only across stimulus identity, but also across certain domains within the auditory and the visual perceptual modalities when the input is meaningfully relevant (Rabagliati et al., 2018). For example, Marcus et al. (2007) showed that, while 7-month-old infants failed to learn rules from non-speech sounds (tones, timbres, animal sounds), they succeeded when previously exposed to the same rules instantiated over speech. Accordingly, Bulf and colleagues (2019) showed that infants can generalize rules extracted from sequences composed of numerical displays to sequences of geometrical shapes (Bulf, Capparini, Nava, de Hevia, & Macchi Cassia, 2019). These studies indicate that infants are able to transfer abstract structures across domains within both the auditory modality (from speech to non-speech sounds, Marcus et al., 2007) and the visual modality (from numerical displays to shapes, Bulf et al., 2019). While infants' ability to generalize across domains provides evidence that RL is not bound to a specific stimulus type, it is still not clear at which level of abstraction infants can represent the acquired rule. Is infants' RL abstract enough to allow for a broad transfer of learning across input modalities, or is RL confined to operate only over specific types of stimuli, and only within each perceptual modality? To address these questions, we investigated infants' ability to generalize abstract structures from vision to speech and vice versa.

Assessing infants' ability to generalize across perceptual modalities is crucial for understanding the level of abstraction of infants' RL, as well as to determine the nature of the underlying mechanisms. For example, the stimulus characteristics that initiate the generalization process, and the representational format of what is being learned, should not be so narrow as to impede the use of prior knowledge, yet not so broad as to override any current learning experience (Urcelay & Miller, 2014; White

& Aslin, 2011). To our knowledge, only one study has investigated generalization of abstract structure across modalities, investigating 8- and 16-month-old infants' transfer of learning to attend to the end of a sequence from vision to speech (Hupp & Sloutsky, 2011). Younger infants were able to generalize the structure within the visual modality, but not from vision to speech; this ability was present in older infants, providing evidence for a developmental trend in infants' transfer of learning. However, infants' abstraction was examined using two-part object sequences, instead of the three-item triplets classically used to assess infants' RL. Moreover, infants were presented with a one-way transfer of learning only, that is, from the visual to the auditory modality, but not vice versa. Yet, speech is a stimulus to which infants are exposed from before birth, and this might support transfer of RL from speech sounds to visual stimuli even in infants younger than 16 months of age (Kovács, 2014; Marcus et al., 2007).

Using a cross-modal RL task, we tested 7-month-old infants' transfer of learning both from speech to vision and from vision to speech. To this end, we used multimodal sequences of visual shapes and speech sounds, capitalizing on prior evidence that infants are able to integrate multimodal information while performing a RL task. For example, 5-month-olds are able to learn an ABB or ABA rule instantiated by audiovisual sequences, while neither auditory nor visual information alone is sufficient to promote infants' RL (Frank et al., 2009). Accordingly, multimodal information (face and voice) boosts 8-month-olds' ability to extract rule-like structure from a sequence of emotional facial expressions (Tusi et al., 2016), and redundant tactile stimulation supports RL of tone patterns in 7-month-olds (Lew-Williams et al., 2019).

In the present study, 7-month-old infants were habituated to audiovisual sequences organized into ABB and ABA rule-governed patterns. Following habituation, they were presented with 6 test sequences alternating the ABB and ABA structure. In Experiment 1 (auditory-visual condition: AV), the habituation sequences included speech sounds organized into ABB or ABA rule-like patterns accompanied by uninformative but coordinated shapes, while in the test sequences the speech sounds were uninformative, and rules were delivered by the visual shapes (Figure 1). In Experiment 2 (visual-auditory condition: VA), infants were habituated to visual rules accompanied by uninformative sounds, and tested with speech rules accompanied by uninformative shapes (Figure 1). Because in both experiments there was a switch in the informative cues delivering the rule (i.e., speech sounds or visual shapes) across the habituation and test trials, infants had to transfer their learning across perceptual domains to be able to discriminate between the familiar and novel rule at test. Successful learning of the familiar rule would be revealed by either a novelty and familiarity preference at test, which would indicate that infants discriminated habituation from test stimuli, and both have been reported in prior RL studies (though novelty preferences are more common; Rabagliati, Ferguson, & Lew-Williams, 2019; see Schonberg et al., 2018, for review).

Furthermore, the identification of individual differences in infants' attention has arisen as an important topic in infant research. Specifically, the amount of time infants spends to familiarize to a given stimulus is considered as a reliable indicator of individual differences in infant attention and information processing skills both in the visual (Colombo et al., 1995) and in the auditory domain (Colombo & Bundy, 1983; Mather, 2013), and it is thought to reflect the modality with which stimulus information is processed. For example, infants with shorter looking times appear to process information more efficiently by focusing on the global aspects of the stimuli, while infants with longer looking times rely on a less efficient piecemeal strategy by focusing on the local information embedded in the stimuli (Cuevas & Bell, 2014; Reynolds et al., 2011). Importantly, looking duration has also been associated with later cognitive performance in childhood, with shorter looking times related to more optimal cognitive outcomes (Colombo, 1993). Thus, by exploring individual differences in familiarization times in the current study we aimed to better characterize the role of infants' attention in the ability to extract higher order structures from a stream of stimuli.

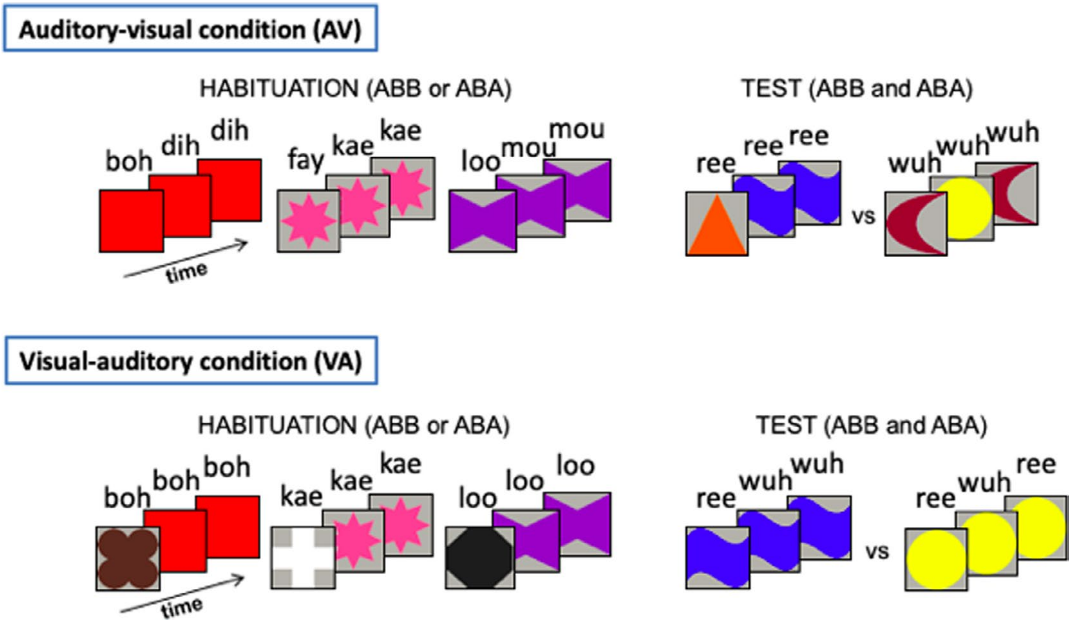

FIGURE 1 Example of stimuli and procedure used in the auditory-visual condition (AV, Experiment 1) and in the visual-auditory condition (VA, Experiment 2)

2 | EXPERIMENT 1

2.1 | Methods

2.1.1 | Participants

A sample of 32 healthy full-term 7-month-old infants (mean age = 238.69 days, *SD* = 24.11 days; 15 females) were recruited for the experiment. Data from an additional 12 infants were excluded from the final sample because of fussiness (*N* = 6), falling asleep (*N* = 3), or lack of interest (*N* = 3). Sample size was determined based on previous work by Bulf et al. (2017) where similar analyses were conducted. All infants included in the final sample were alert and engaged during both learning and test. Infants were recruited by letter and telephone form hospital records and were given a small gift (a toy or baby T-shirt) for their participation. The protocol was carried out in accordance with the ethical standards of the Declaration of Helsinki (BMJ 1991; 302:1194) and was approved by the University of California Institutional Review Board (ID #10-000619—"Brain Mechanisms of Visual Development"). Parents gave written informed consent for their infants' participation before data collection.

2.1.2 | Stimuli, apparatus and procedure

Auditory stimuli consisted of recordings of 12 syllables (boh, dih, fay, ji, kae, loo, mou, noi, ree, she, tir, and wuh; M duration = 352 ms), presented in coordination with visual stimuli. Visual stimuli consisted of 12 colored shapes (green arrow, purple bowtie, yellow circle, brown clover, maroon crescent, cyan diamond, blue flag, grey octagon, white plus, red square, pink star, and orange triangle).

Shapes were organized into triplets and presented one at a time from left to right: The first shape was displayed on the left side of the monitor for 400 ms, the second shape was displayed in the middle of the monitor for 400 ms, and then, the third shape was displayed on the right side of the monitor for 1000 ms. A blank screen (500 ms) separated the triads presentation on each trial. When viewed from a distance of 60 cm, each shape was embedded in a virtual square of 10.2° × 10.2° of visual angle, and the distance between the centers of adjacent figures was 11.2°. Infants sat on a parent's lap approximately 60 cm from the stimulus presentation monitor. A Dell OptiPlex 7040 computer and ViewSonic VX2268wm 22-inch monitor were used to present the stimuli and to collect looking time data. An experimenter viewed the infant on a second monitor and coded looking times online by pressing a key when the infant was looking. The experimenter was blind to the stimulus being presented on screen.

Infants were habituated to ABB or ABA triplets (counterbalanced across infants) in which the rule was delivered by speech sounds accompanied by uninformative (i.e., identical) shapes (auditory-visual condition: AV; Figure 1). Four unique syllables were assigned to the A group and four to the B group during the habituation phase. The A and B syllables were randomly combined by the software to generate 16 different ABB triads (i.e., a shape A was followed by a different shape B, which was in turn followed by the shape A) and 16 different ABA triads. Each trial began with the presentation of an engaging attention-getter (an animated cartoon with sound). Once the experimenter determined that the infant was looking at the monitor, he or she pressed a key and stimulus presentation began. In each trial, sequences of three items were presented in random order until the trial ended. When infants turned away from the monitor, the experimenter released the key press and stimulus presentation was immediately paused. If the infant returned attention toward the screen, the experimenter again pressed the key and stimulus sequences resumed. Only looking time at the stimuli (not time spent looking away) was included in the measured length of a habituation trial. Each trial was presented until 60 s looking time was accumulated or the infant continuously looked away for 2 s. Infants were intended to be habituated when their looking times across four consecutive trials declined to <50% of looking time during the first four trials or until they received a maximum of 12 trials.

Following habituation, infants were presented with 6 test trials in which ABB and ABA rules were presented alternately, each for three times. In the test phase, syllables were uninformative and rules were delivered by 4 unique visual shapes, two assigned to the group A and two assigned to the group B, randomly combined to generate 4 different ABB/ABA triads. The order of presentation (i.e., novel rule or familiar rule first) was counterbalanced among infants. Test trials were terminated after 2 s of continuous looking away or a maximum of 60 s of looking time. Looking time (s) towards novel and familiar rules was considered as the dependent variable.

2.2 | Data analysis

Preliminary data inspection revealed that looking times recorded during the test phase was not normally distributed for all test trials (Ws > 0.69, *p*s < 0.001). Thus, after Csibra et al. (2016), data were logarithmically transformed before performing all statistical analyses. In order to explore the role of habituation times on infants' looking behavior at test, a Pearson bivariate correlation was performed between total looking times during habituation and novelty preference score at test. Novelty preference score was computed as total looking to the novel test sequences divided by total looking to familiar and novel sequences combined. Like previous studies exploring individual differences in habituation times (Colombo et al., 1995; Frick & Colombo, 1996; Jankowski & Rose, 1997; Reynolds et al., 2011), a median split (175.57 s; *SD* = 90.45) was used to divide infants in a group of short habituators and a group of long habituators on the basis of their total looking times during habituation.

Thus, a repeated-measures analysis of variance (ANOVA) was performed on log-transformed looking times at test, with habituation rule (ABB, ABA), habituation condition (long, short habituators) and first test trial (novel, familiar) as between-subjects factors, and test trial pair (first, second, third) and test stimulus (novel, familiar) as within-subjects factors. All statistical analyses were performed using the R-based open-source software Jamovi v1.6 (https://www.jamovi.org) and conducted on a 0.05 level of significance (two-tailed). Pairwise comparisons were performed by applying *t*-tests and the Fisher's least significant difference procedure (Howell, 2012), and Holm–Bonferroni correction was used where appropriate (Abdi, 2010). The Greenhouse–Geisser correction for non-sphericity was used to adjust degrees of freedom as appropriate. Effect sizes were estimated using the η_p^2 measure, and the data are reported as means and standard deviations (SDs). Following recent recommendations on best practices in infant looking-time research (Oakes, 2017), in order to strengthen our results we also performed Bayesian analyses in Jamovi 1.6 (https://jamovi.org) by using the default Cauchy prior ($r = 0.707$). Using the Jamovi formalism, the index next to the Bayes Factors (BF) indicates that the null hypothesis (H_0) is in the denominator and the alternative hypothesis (H_1) is in the numerator. Thus, BF_{10} is $p(\text{data}|H_1)/p(\text{data}|H_0)$, with $BF_{10} > 10$ considered as strong evidence for an effect, and $3 < BF_{10} < 10$ considered as moderate evidence.

2.3 | Results

2.3.1 | Habituation phase

Infants viewed an average of 9.09 habituation trials (*SD* = 2.36, range: 5–12). Nine infants (5 long habituators) failed to meet the habituation criterion in 12 or fewer trials. A paired-sample *t*-test was conducted to compare mean looking times over the first four ($M = 28.61$ s; $SD = 11.01$ s) and the last four ($M = 12.56$ s; $SD = 4.43$ s) habituation trials. The comparison attained statistical significance, $t(31) = 11.10$; $p < 0.001$, $d = 1.96$, confirming the presence of a significant decrease in infants' attention across the habituation phase.

2.3.2 | Test phase

Correlational analysis between total looking times during habituation and novelty preference scores at test showed a significant negative association, with shorter habituators showing higher novelty preference scores, $r(32) = -0.38$, $p = 0.04$, $d = 0.82$ (Figure 2). In order to compare infants with total habituation times above ($N = 16$) versus under ($N = 16$) the median, a repeated-measures ANOVA on log-transformed looking times at test revealed a main effect of test trial pair, $F(2, 48) = 7.49$, $p = 0.001$, $\eta_p^2 = 0.24$, that was due to longer looking times during the first trial pair ($M = 14{,}694$ ms, $SD = 9{,}617$ ms) compared to the second ($M = 11{,}428$ ms, $SD = 7{,}497$ ms) $t(31) = 2.32$, $p = 0.03$, $d = 0.41$, and the third trial pair ($M = 9{,}638$ ms, $SD = 9{,}173$ ms), $t(31) = 3.04$, $p = 0.005$, $d = 0.54$. This main effect was qualified by a test trial pair by test stimulus by first test trial by habituation condition interaction, $F(2, 48) = 3.30$, $p = 0.046$, $\eta_p^2 = 0.12$. No other main effects or interactions attained statistical significance (all *p*s > 0.06).

The 4-way interaction was explored with two separate ANOVAs, one for each habituation condition (i.e., short and long habituators), with test trial pair and test stimulus as within-subjects factors and first test trial as between-subjects factor. For the short habituator subsample, there was a significant test stimulus main effect, $F(1, 28) = 7.84$, $p = 0.014$, $\eta_p^2 = 0.36$, with participants looking longer

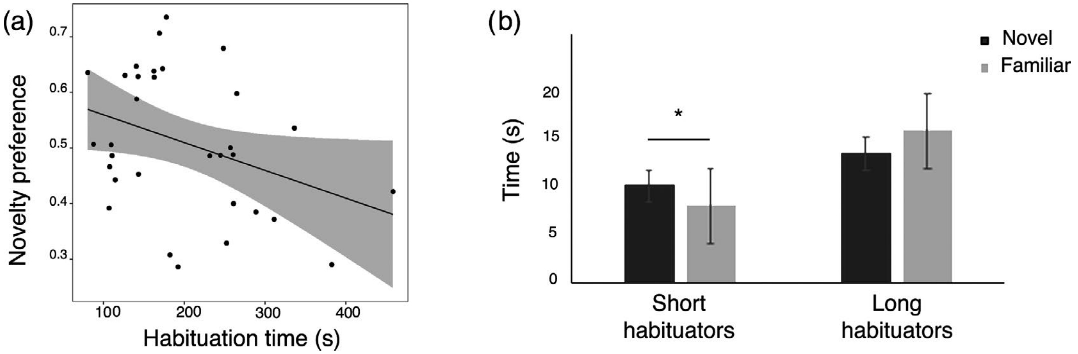

FIGURE 2 AV condition: (a) correlation between habituation looking times and novelty preference score at test; (b) mean looking times (±*SE*) to the familiar and novel test trials in the short habituators and long habituators groups

to novel ($M = 10{,}183$ ms, $SD = 4{,}021$ ms) than to familiar ($M = 8{,}105$ ms, $SD = 3{,}768$ ms) test trials (Figure 2). A two-tailed paired sample Bayesian t-test confirmed the results obtained from frequentist analysis, showing moderate evidence for a difference between novel and familiar test trials in the short habituators subsample ($BF_{10} = 3.26$). No other main or interaction effects attained statistical significance (all $ps > 0.13$).

For the long habituator subsample, there was a significant test trial pair main effect, $F(2, 28) = 4.49$, $p = 0.02$, $\eta_p^2 = 0.24$. Post-hoc comparisons revealed that it was due to longer looking times during the first ($M = 18{,}131$ ms, $SD = 10{,}952$ ms) compared to the third ($M = 12{,}138$ ms, $SD = 12{,}157$ ms) trial pair ($p = 0.019$). The main effect was qualified by a test trial pair by test stimulus by first test trial interaction, $F(2, 28) = 5.27$, $p = 0.01$, $\eta_p^2 = 0.27$. However, post-hoc comparisons did not reveal significant differences in looking times within test trial pairs (all $ps > 0.57$). No other main or interaction effects attained statistical significance (all $ps > 0.18$). As in the short habituator group, two-tailed paired sample Bayesian t-tests further confirmed the lack of significant results emerged from the frequentist analysis, showing anecdotal evidence for the lack of difference between novel and familiar test trials in the long habituators subsample ($BF_{10} = 0.51$).

3 | EXPERIMENT 2

3.1 | Methods

3.1.1 | Participants

The final sample consisted of 32 healthy full-term 7-month-old infants (mean age = 235.13 days, *SD* = 27.42 days; 16 females) were recruited for the experiment. Five additional infants were tested but excluded from the final sample because of fussiness (*N* = 3) or lack of interest (*N* = 2). As in Experiment 1, all infants included in the final sample were alert and engaged during both learning and test. Infants were recruited by letter and telephone from hospital records and were given a small gift (a toy or baby T-shirt) for their participation. As for Study 1, the protocol was carried out in accordance with the ethical standards of the Declaration of Helsinki (BMJ 1991; 302:1194) and was approved by the University of California Institutional Review Board (ID #10-000619—"Brain Mechanisms of Visual Development"). Parents gave written informed consent for their infants' participation before data collection.

3.1.2 | Stimuli, apparatus, and procedure

Stimuli, apparatus, and procedure were the same as in Experiment 1, with the exception that for infants in this experiment, the habituation rule was delivered by visual shapes accompanied by uninformative (identical) speech sounds (visual-auditory condition: VA; Figure 1). Four unique shapes were assigned to the A group and four to the B group during the habituation phase. The A and B images were randomly combined by the software to generate 16 different ABB triads (and 16 different ABA triads. In the test phase, infants were presented with ABB and ABA test sequences in which visual shapes were uninformative and rules were delivered by 4 unique syllables, two assigned to the group A and two assigned to the group B, randomly combined to generate 4 different ABB/ABA triads.

3.2 | Data analysis

The statistical analyses were the same as in Experiment 1. Preliminary data inspection revealed that looking times recorded during the test phase were not normally distributed for all test trials also in Experiment 2 (Ws > 0.58, *p*s < 0.005). Thus, after Csibra et al. (2016), data were logarithmically transformed before performing all statistical analyses.

In order to explore the role of habituation times on infants' looking behavior at test, a Pearson bivariate correlation was performed between total looking times during habituation and novelty preference score at test. Moreover, as in Experiment 1, the infants' sample was subsequently split into two groups of short ($N = 16$) and long habituators ($N = 16$) based on median total habituation time (180.00 s; $SD = 84.13$ s). To determine whether infants' looking times during test trials differed for the novel and familiar order, log-transformed looking times at test were entered into a five-way repeated-measures ANOVA with habituation rule (ABB, ABA), habituation condition (long, short habituators) and first test trial (novel, familiar) as between-subjects factors, and test trial pair (first, second, third) and test stimulus (novel, familiar) as within-subjects factors.

3.3 | Results

3.3.1 | Habituation phase

During habituation, infants viewed an average of 8.31 trials ($SD = 2.32$, range: 6–12). Six infants (5 long habituators) failed to reach the habituation criterion. As in Experiment 1, a paired-sample t-test confirmed that infants' looking times decreased significantly from the first ($M = 31.47$ s; $SD = 13.24$ s) to the last habituation trials ($M = 14.38$ s; $SD = 6.66$ s), $t(31) = 8.31$; $p < 0.001$, $d = 1.47$, thus showing the predicted habituation pattern.

3.3.2 | Test phase

The Pearson bivariate correlation performed between total looking times during habituation and the novelty preference score at test proved nonsignificant, $r(32) = 0.09$, $p = 0.61$, $d = 0.18$ (Figure 3).

The ANOVA performed on log-transformed looking times at test, with habituation rule (ABB, ABA), habituation condition (short, long habituators), and first test trial (novel, familiar) as between-subjects factors, and test trial pair (first, second, third) and test stimulus (novel, familiar) as within-subjects factors revealed a significant test trial pair by habituation rule by habituation condition interaction, $F(2, 48) = 3.87$, $p = 0.03$, $\eta_p^2 = 0.14$. No other main effects or interactions attained statistical significance (all ps > 0.11). The 3-way interaction was explored with two separate ANOVAs, one for each habituation condition (i.e., short and long habituators), with test trial pair as within-subjects factor and habituation rule as between-subjects factor. However, both for the short and the long habituator subsamples no main or interaction effects attained statistical significance (all ps > 0.12). In order to match analysis performed in Experiment 1, two-tailed paired sample Bayesian t-tests were performed to explore the possible differences between novel and familiar test trials in the short and long habituators subsamples. These analyses further confirmed the lack of significant results emerging from the frequentist ANOVA as low BF_{10} values (all $BF_{10} < 0.34$) were found for both the short and long habituators subsamples (Figure 3).

4 | GENERAL DISCUSSION AND CONCLUSIONS

The present study aimed at investigating 7-month-olds' ability to extract high-order rules from a sequence of stimuli and to transfer learning across the auditory and visual modalities. Furthermore, the role of individual differences in infants' attention in their ability to generalize learned patterns to new items was explored.

Results highlight the role of habituation times in infants' learning of rule-like structures. Infants with short habituation times were able to learn and transfer the rule instantiated by speech sounds to the visual modality (AV condition), while long habituators did not show any evidence of RL transfer. In contrast, 7-month-olds provided no evidence of RL transfer from visual shapes to speech sounds (VA condition), irrespective of the length of their habituation time. It should be noted that our task does not disentangle whether in the VA condition infants were not able to detect the rule presented during the habituation phase, or whether they have learned the habituation rule but were not able to generalize it to the stimuli presented in the test phase. Future studies should address this issue.

In line with previous studies that explored individual differences in habituation time (e.g. Colombo, 1993; Colombo et al., 1995; Flom et al., 2018; Johnson et al., 2004), our data suggest that the ability to generalize the learned rule from speech sounds to visual shapes is constrained by infants' ability to efficiently process the item sequences presented during habituation. Overall, these results suggest that 7-month-old infants are able to transfer the learning of a high-order rule between different sensory

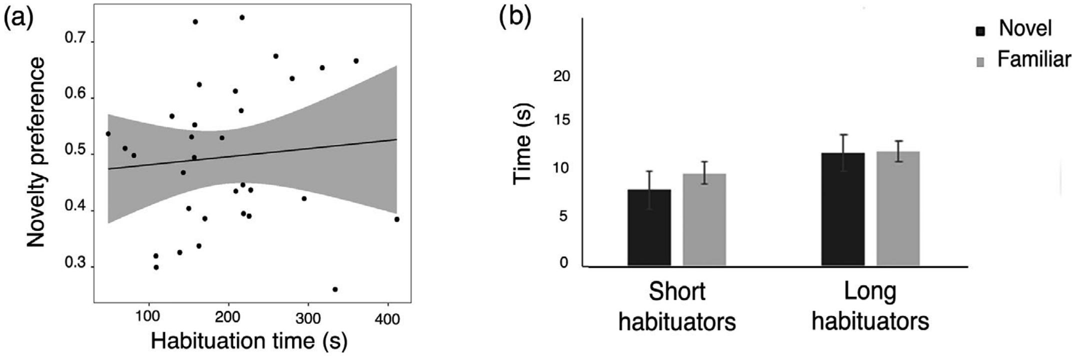

FIGURE 3 VA condition: (a) correlation between habituation looking times and novelty preference score at test; (b) mean looking times (±*SE*) to the familiar and novel test trials in the short habituators and long habituators groups

modalities, but the ability is constrained by the nature of the stimulus to be learned and by the efficiency of the learner.

The speech advantage in infants' RL generalization is not due to a general advantage in processing speech over visual rules. Indeed, 7-month-olds are able to extract and generalize a repetition-based rule within both the auditory and the visual modalities, that is, from sequences of speech sounds (Marcus et al., 1999) and sequences of visual shapes (Bulf et al., 2017), respectively. Moreover, within each modality 7-month-olds are able to generalize RL across domains, that is, from speech to non-linguistic sounds (tones, timbres, animal sounds; Marcus et al., 2007), and from numerical visual displays to non-numerical visual stimuli (geometrical shapes; Bulf et al., 2019). However, the present study shows that transfer of RL occurs only when infants with short habituation times acquired the rule from speech, but not when rule acquisition was based on visual sequences, a result that is in line with recent evidence that 8-month-old infants cannot generalize an abstract relation from the visual domain to the linguistic domain (Hupp & Sloutsky, 2011). This advantage of speech suggests that the underlying representation may be broader/more abstract when a rule is acquired from language than from visual elements, at least at 7 months of age. This abstract representation, however, is likely relatively independent from the auditory modality through which it has been acquired, and thus integrates cross-modal information (Barnett & Ceci, 2002; Conway & Christiansen, 2005), allowing for the generalization of the learned rule to a different perceptual modality. Moreover, the abstract rule representation generated from speech sequences is also likely flexible, as it applies both to simpler ABB rules (involving an adjacent repetition), and to more complex ABA rules (involving a non-adjacent repetition; Johnson, 2009; Rabagliati et al., 2012).

The broad nature of rule representation engendered by linguistic information might derive from infants' expertise with language. As suggested by Dawson and Gerken (2009), with development, RL might become tuned to those stimuli to which infants are most frequently exposed in their environment. This would provide an advantage in learning abstract rules from these categories of stimuli as compared to more unfamiliar stimuli. This is consistent with studies showing that highly experienced stimuli, such as faces (Bulf et al., 2015) and images of familiar animals (Saffran et al., 2007), would enhance 7-month-olds' RL abilities. Because 7-month-old infants are exposed to language from before birth, patterns in speech sounds may be more readily represented and categorized than geometrical shapes. This, in turn, would create more flexible and abstract representations, perhaps by reducing memory and attentional load required to process each individual stimulus in the sequence (Wierzchon et al., 2012).

Alternatively, the role of speech in infants' RL might be rooted in genetically determined computational modules (Marcus et al., 1999, 2007). This hypothesis would rest on the assumption that language acquisition mechanisms are part of a cognitive specialization for language and are unique to humans (Pinker, 1991). However, infants' ability to extract and generalize abstract rules seems to be a domain-general learning mechanism that is available to be used on either linguistic and non-linguistic materials (Dawson & Gerken, 2009; Saffran et al., 2007), and shared with non-human animals (Hauser et al., 2002; de La Mora & Toro, 2013; Santolin et al., 2016); this casts doubts on the claim that RL is a language-specific mechanism.

Another possibility is that the speech advantage is a product of the rich, redundant cues provided by speech sounds (e.g., syllable identity, individual phonemes, and other phonetic features, Thiessen, 2012). While this possibility cannot be excluded, it is worth noting that, in the current study, visual sequences provided infants with redundant cues as well (e.g., shape identity, color, and spatio-temporal information). Moreover, in previous studies infants were able to extract and generalize rules from speech sounds (Marcus et al., 1999) and visual shapes (Bulf et al., 2017) at the same level of rule complexity – that is, both ABB adjacent and ABA non-adjacent repetitions; this as well renders the redundant-information hypothesis unlikely. Future research should further investigate whether the speech advantage in infants' RL is driven by infants' expertise with language, for example, by testing infants younger than 7 months of age. Indeed, 4-month-olds can learn repetition-based rules in music that 7-month-olds do not (Dawson & Gerken, 2009) providing evidence that RL is not necessarily tuned to language early in development.

In summary, the present study provides preliminary evidence that individual differences in infants' visual attention play an important role in shaping the ability to transfer the learning of higher order structures embedded in multimodal stimuli from the auditory to the visual modality. However, current results are to be regarded as preliminary, and need to be confirmed by further replication in larger samples.

Regardless of the interpretation of the observed asymmetry in infants' transfer of RL between the linguistic and visual modalities, our findings demonstrate that language has a critical role in 7-month-olds infants' RL abstraction and generalization across perceptual modalities. Our data do not shed light on how prior experience with language changes the ways learners encode new information/rules, or the ways they retrieve new information/rules (Urcelay & Miller, 2010). Moreover, the degree (specificity vs generalization; Aslin, 2011) and nature (symbolic vs. repetition-based; Endress et al., 2005) of abstraction in infants' RL, and its role in language acquisition, remain largely unknown. Future research shall address these questions by exploring individual differences in the development of RL abilities.

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