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Developmental Invariance in the Statistical Learning of Target Location Probability*

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위치 확률단서 학습에서의 발달불변성

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ABSTRACT

Regularities in the learning environment allow us to make predictions and guide behavior. Growing evidence of location probability learning (LPL) demonstrates that the statistical regularity of target locations affects spatial attention allocation. However, existing studies on LPL mostly focus on learning in adults. To achieve a comprehensive understanding of the mechanism of LPL, we investigated the effect of target location probability on visual search in children aged 5 to 9 years compared to adults. Both children and adults responded faster when the target appeared in the high probability "rich" quadrant than in the low probability "sparse" quadrants of the search space. Importantly, the magnitude of the bias was constant across participants of various ages and not dependent on individual differences in executive functions. These results provide novel evidence that implicit statistical learning of target locations occurs early in development and remains stable until early adulthood and this is a distinct developmental pattern from learning of explicit goal-driven spatial attention.

주요어 : location probability learning, statistical learning, implicit learning, development

The allocation of attention in space is guided not only by stimulus salience and task demands but also by an observer's past experience. Locations that have frequently contained a visual search target in the past are prioritized in attentional allocation as well as search behavior, which is called "location probability learning" (LPL) (Geng & Behrmann, 2002; Jiang, Swallow, & Rosenbaum, 2013; for a review, see Jiang, 2018). Recent studies have shown that this learned spatial bias in visual search is unimpaired even in older adults and patients with Parkinson's disease (Sisk, Twedell, Koutstaal, Cooper, & Jiang, 2018; Twedell, Koutstaal, & Jiang, 2017); thus, it was suggested as a compensating attention process for other attentional deficits induced by aging and neurocognitive disease. A complete understanding of LPL should include an understanding of its developmental origins. However, to our knowledge, only two studies have tested LPL in younger participants, which were used only as a control to evaluate autistic children's visual search performance (Jiang, Capistrano, Esler, & Swallow, 2013; Pellicano et al., 2011). Their core findings on the nature of LPL were not congruent. Therefore, in the current study, we examined when children show adult-like LPL and how it is related to the children's age and their development-dependent learning factors (e.g., selective attention and working memory) to examine the nature of LPL.

The Effects of Past Experiences on Attention Orienting

LPL has been demonstrated in the visual search paradigm, where the probability of a target appearance was higher in a specific quadrant of the searching space (i.e., the "rich" quadrant). When participants were asked to search for a target (e.g., left-right-tilted T) among distractors (e.g., rotated Ls), they gradually responded faster to the target presented in the rich quadrant. Facilitation in reaction times for the rich quadrant was also observed in the subsequent unbiased phase where a target appeared in all quadrants with equal probability (Jiang et al., 2013) and persisted for at least a week after learning (Jiang, Swallow, Rosenbaum, & Herzig, 2013), suggesting that this spatial bias is more likely to be a result of attentional learning than short-term inter-trial facilitation.

A key characteristic of LPL that has been suggested is that this attention bias would be acquired without the intention or explicit awareness of learners. That is, most participants in LPL studies did not notice the biased spatial distribution of target stimuli (Geng & Behrmann, 2002; Jiang et al., 2013). In addition, few participants who correctly identified the rich quadrant did not show greater LPL than those who did not recognize the uneven target distribution (Twedell et al., 2017). Although a recent meta-analysis has questioned the implicit nature of LPL and suggested a relation between awareness and LPL (Vadillo, Linssen, Orgaz, Parsons, & Shanks, 2020), LPL still contains considerable features of implicit learning in general.

Generally, implicit learning has been hypothesized to have five distinguishing features from explicit learning (Reber, 1989): (1) developmental invariance (Drag & Bieliauskas, 2010; Finn et al., 2016), (2) robustness to disease or injury (Reber, 2013; Reber, Martinex, & Weintraub, 2003), (3) specificity of transfer (Manza & Reber, 1997), (4) IQ independence (Atwell, Conners, & Merrill, 2003; Bussy, Charrin, Brun, Curie, & des Portes,2011), and (5) secondary task independence (Curran & Keele, 1993; Hayes & Broadbent, 1988). That is, implicitly acquired knowledge tends to be inflexible, perceptually bound to the training context, and remains intact with regard to aging, developmental maturation, neurological/psychological disorder, and lack of attentional resources. For example, Finn and her colleague (2016) measured multiple forms of implicit and explicit learning ability for 10-year-old children and adults. They observed adult-levels of implicit learning such as probabilistic classification and artificial grammar learning but lower explicit learning levels from the children (Finn, Kalra, Goetz, Leonard, Sheridan, & Gabrieli, 2015). Brain lesion studies have documented that several forms of implicit learning are preserved in amnesic patients (Meulemans & der Linden, 2003; Nosofsky, Denton, Zaki, Murphy-Knudsen, & Unverzagt, 2012; Reber, Martinez, & Weintraub, 2003) despite the severe impairment of explicit memory in these patients.

Likewise, LPL has been shown to be persistent and task specific (Jiang, Swallow, Won, Cistera, & Rosenbaum, 2015; Salovich, Remington,& Jiang, 2018), and robust to left hemifield neglects (Geng & Behrmann, 2002), autistic spectrum disorder (Jiang et al., 2013), aging (Twedell et al., 2017), and Parkinson's disease (Sisk et al., 2018), as well as secondary task interference (Won & Jiang, 2015). However, the developmental trajectory of LPL has not been examined empirically.

Development of experience-driven attention process

Studies focusing on the development of attentional processes have revealed different maturation timeline of top-down (feedback, goal-driven, executive) and bottom-up (feedforward, reflexive) processes. For example, in difficult visual search, as in a conjunction search, 6-year-old children showed slower response times at searching for the target (Donnelly, Cave, Greenway, Hadwin, Stenvenson, & Sonuga-Barke, 2007). In contrast, when the dissimilarity between a target and distractors increased, i. e., when the task difficulty decreased, even young infants (Adler & Orprecio, 2006) and 6-year-old children successfully searched a target (Donnelly et al., 2007). However, as was mentioned above, the developmental trajectory of a recently proposed source of attentional bias, namely "experience-driven," has not been examined. Despite the fact that two studies have reported LPL in children aged 5 - 13 years (Jiang et al., 2013; Pellicano et al., 2011), their focal research interest was not in understanding the development of LPL itself but in demonstrating spared LPL in autistic children. Thus, these studies neither included a sufficient number of children with a proper age range to detect age-related changes nor compared their learning to adults'. It is still unknown whether there are any developmental changes in LPL, and when and how children acquire adult-like experience-driven attention learning.

Similar questions have been raised and discussed in the contextual cueing paradigm. Visual search is improved when target-distractor configurations are repeated (Chun & Jiang, 1998; Sisk, Remington, & Jiang, 2019). Although the participants learn the target-context association instead of a general spatial bias in the contextual cueing, its learning shows similar characteristics to LPL. For example, both types of learning are mostly implicit and the learning effect persisted even one-week after learning (Chun & Jiang, 2003; Jiang, Swallow, Rosenbaum, & Herzig, 2013). Also, the transfer of learning was specific to item color or task difficulty during learning (Jiang & Song, 2005a) as well as task similarity between learning and testing (Jiang & Song, 2005b). This contextual cueing effect has been consistently observed in various conditions, but developmental studies with school-aged children have reported conflicting findings. For example, Vaidya, Huger, Howard, and Howard (2007) did not find the cueing effect with 10 year-old-children when the subjects were instructed to find a target (T) among multiple Ls (T-and-L paradigm). In contrast, Dixon, Zelazo, and De Rosa (2010) reported contextual cueing in children aged 5 - 9 years using age-appropriate stimuli and a touching response device. These results indicate that with age-appropriate stimuli and experimental setting, young children could learn and use spatial context. Meanwhile, using the standard T-and-L task, Couperus, Hunt, Nelson, and Thomas (2011) demonstrated that 10-year-old children's contextual learning was modulated by the ratio between attended and unattended stimuli, in contrast to the robust contextual cueing effect of the adult participants irrespective of attention setting. Additionally, children aged 6–8 years failed to show an adult-like contextual cueing effect when the ratio between the repeated and non-repeated display was low (Yang & Merrill, 2015). These results suggest that although the basic contextual learning mechanisms may be available early in development, development-dependent learning factors such as available resources of selective attention and working memory may play an important role in the expression of young children's implicit learning.

Developmental Hypotheses

Given the similarity between LPL and contextual cueing, we may expect to see a similar early developmental onset of basic spatial learning mechanisms with less robustness of the system. However, LPL is distinguished from contextual cueing, in which participants acquire a general spatial attention bias based on simple frequency of target location, but not a higher order target-distractor configuration association that is necessary for predictive use of context. It should be considered that object location is spontaneously encoded and remembered even when it is not task relevant (Foster, Bsales, Jaffe, & Awh, 2017; Schneegans & Bays, 2017), but effective encoding of spatial displays has been suggested to require selective attention. Indeed, under reduced attention, when the similarity among a target and distractors increased, adult participants' contextual learning was attenuated (Jiang & Chun, 2001). However, LPL was not affected under reduced attention (Won & Jiang, 2015). Thus, we presume that such a difference in the underlying learning mechanism between LPL and contextual cueing may lead to a different developmental trajectory.

The Current Study

In the current study, we first investigated whether LPL appears early in childhood and is maintained at a constant level across development as predicted by the evolutionary model of implicit learning (Reber, 1989), or whether it gradually develops as children's underlying neural and cognitive architectures mature as predicted by the parallel developmental change model between implicit and explicit learning (Thomas et al., 2004). Hence, we included children from various ages between 5 to 9 to increase sensitivity to the detection of developmental differences and compared their performances to the adults'. We chose this wide age range because there is no benchmark from other previous studies on how young the effects of LPL might emerge and how old adults-level LPL might approach. Therefore, we started with children as young as five, as a previous contextual cueing study (Dixon et al., 2010) demonstrated a similar effect of past experience on the same aged children's visual search. We set the upper limit of 9 because children's visual search performance may approach adults levels at around ten years of age, including little changes of subsequent years (Klenberg, Korkman & Lahti-Nuuttila, 2001). Besides, we evaluated whether children's LPL would be influenced by development-dependent learning factors, such as executive function and memory, as shown in the young children's contextual cueing learning (Yang & Merill, 2015).

Research Question 1. Does LPL appear early in childhood and is maintained at a constant level across development?

Research Question 2. Would development-dependent learning factors influence children's LPL?

Methods

Participants

A total of 49 typically developing children ages 5.04 - 9.21 years (34 boys, 29 girls; M_{age} = 6.99 years, SD = 1.15 years) and 22 healthy adults (14 men, 8 women; M_{age} = 22.14 years, SD = 2.17 years) participated in the experiment. We split the children into two age groups: 5 - 6-year-olds (i.e., preschoolers, N = 26) and 7 - 9-year-olds (i.e., school-aged, N = 23). An additional fourteen children participated but were excluded from analysis because of failure to complete the experiment. Based on medium effect size (f = .25), an alpha level of 0.05 and power of 0.95 for repeated measures ANOVA with 2 x 3 within-between interactions, a total sample size of N = 66 was calculated to be necessary using G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007). A medium effect size (.25) was chosen because previous contextual cueing studies that had similar task structures either reported no age-related differences between adults and children or a very small effect size of η_p^2 = .089 (Yang & Merrill, 2015). We increased the sample size of adults following an anonymous reviewer's advice. Both adults and children were recruited through advertisements in the neighborhood of Daegu. Adult participants and the parents of child participants provided written consent before the experiment and the children provided verbal assent. All participants had a normal or corrected-to-normal visual acuity and normal color vision, and they were compensated $10-15 for their participation. All experiments in the current study were approved by the Institutional Review Board of Korea Brain Research Institute.

Stimuli and Apparatus

The experiment was conducted on a 21.5-inch touch monitor with resolution of 1920 × 1080. Participants sat in front of the monitor at their own comfortable distance. MATLAB 2018a with Psychophysics Toolbox (Brainard, 1997) was used to program the experiment. All stimuli were presented on a black background (RGB: 0, 0, 0). The search items were three different cartoon characters with a single-hand-up position or a hands-around-shoulders position. The characters with a hands-around-shoulders position were the targets and the characters with a hand-up position were the distractors. Each display contained a single type of character with one target and seven distractors. Each stimulus subtended 110 px × 110 px. (We report the item size in pixels, not the visual angle, because the distance from the monitor to the participants was not strictly controlled.) The display was divided into a 6 × 6 invisible matrix, and each cell was sized 130 px × 130 px. A white cross with a size of 20 px × 20 px was used as a fixation point. Nine cells were allocated to the quadrants. Two cells were randomly selected from each quadrant as item locations. Each item was positioned at the center of the selected cell with a random horizontal or vertical jitter within ±10 px. On the search screen, a progress bar to show accumulated correct responses during each

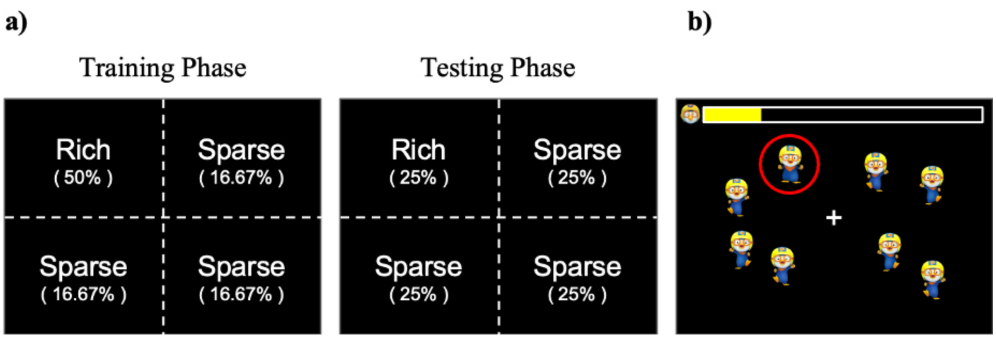

Figure 1. a) Schematic description of the experimental design. The statistical distribution of the training and the testing phase. The display was divided into invisible quadrants. The rich quadrant location was counterbalanced across the participants. b) Search display example. The character with a hands-around-shoulders position was a target in this example (the red circle on the target was not shown in the experiment). The items are not drawn to scale.

session was presented as shown in Figure 1b. The progress bar consisted of a character's small head at the left side (size: 80 px × 80 px) and a white rectangle frame (1730 px × 60 px). The frame was filled with a yellow square as the participants correctly found the target. The center of the progress bar was 50 px apart from the top edge.

Procedure

Twenty-four practice trials were given before the main experiment. The main experiment consisted of three sessions to see the time-course change in the magnitude of LPL. Each session contained six blocks, in which the first five blocks were the training phase and the last block was the testing phase. Each block had 24 trials. Each trial started with a fixation cross for 500 ms, then eight search items appeared. The participants searched for a target (hands-around-shoulders character) among distractors (single-hand-up characters) and responded by touching the target. They were instructed to respond as quickly and accurately as possible. Feedback was provided with a smiling face for a correct response for 300 ms and with a frowning face for an incorrect response for 400 ms. After the feedback, the progress bar showing accumulated correct responses was presented for 500 ms on the blank screen. The length of the inter-trial interval was 1,000 ms.

Each session started with presenting a new character comprising the target and distractors during the session. The order of the three characters were counterbalanced across participants. During the training phase, unbeknownst to the participants, a target was presented at a designated rich quadrant in 50% of trials (see Figure 1a). In the remaining 50% of trials, the target was evenly distributed to three other quadrants with equal probability (16.67% each). The location of the rich quadrant was counterbalanced across participants but was kept constant across sessions within participants. During the testing phase, every quadrant contained a target with an equal probability (25%). The purpose of the testing phase was to test whether the spatial bias in the training phase represented long-term statistical knowledge or short-term inter-trial priming. To keep consistency, although the target was evenly distributed in the searching space during the testing phase, the quadrant was named following the location of the rich/sparse quadrant in the training phase.

At the end of the search task, we asked three questions to verify the participants' awareness of location probability of targets. First, the participants were asked whether they have noticed any rule during the experiment. Regardless of their answer, they were required to state the rule that they conjectured and then to guess the quadrant where the target frequently appeared. The answers were recorded by an experimenter. The participants who successfully noticed unequal probability distribution of targets across quadrants and who correctly indicated the rich quadrant in the last question were excluded from final analyses. Following the search task, to measure children's executive function and memory, the children were tested in four additional tasks - List Sorting Working Memory (LSWM), Picture Sequence Memory (PSM), Flanker Task, and Dimensional Change Card Sorting (DCCS) - among the NIH toolbox cognitive battery (Weintraub et al., 2013). The NIH toolbox cognitive battery was administered on a 10.5-inch iPad Pro. The order of tasks was pseudo-randomized across participants. Although the tasks were computerized, an experimenter presented task instructions orally to the children and monitored their performance. Corrected standard scores with a standardized mean of 100 (*SD* = 15) were used for the analyses.

LSWM (List Sorting Working Memory)

In this task, the children were shown a list of stimuli both visually and auditorily on the iPad, and then they were asked to repeat all of the stimuli back to the experimenter in order of increasing real-world size, from smallest to largest. The children were first shown a list with two items; if they succeeded on this two-item list, the length of the list increased by one item, up to a total seven-item list. If the children failed on a given trial, they received another trial with the same length of list, and if they failed on that trial again, the test was terminated. The number of stimuli in the final list that the children successfully recalled provides a measure of working memory capacity.

PSM (Picture Sequence Memory)

This task measures children's episodic memory retrieval. Color-illustrated sequences of pictures were shown to the children in the center of the iPad screen in a fixed order. When each picture appeared, the experimenter briefly described it. Once all the pictures of the sequence were displayed the pictures were randomly distributed at the center of the screen. The children were instructed to locate all the pictures in their proper position of the sequence to reproduce the correct order. The length of the sequence that the children were asked to order was determined by their age.

Flanker Task

This task was included to measure children's inhibitory control in the context of selective visual attention. Participants were required to indicate the left-right orientation of a centrally presented stimulus with corresponding button pressing on the screen, while inhibiting surrounding stimuli (i.e., flankers) that had either congruent or incongruent orientation to the central stimulus. The task contains an easier version (fish stimuli) and a more difficult version (arrow stimuli) depending on the children's age. Changes in response time from the congruent trials to the incongruent trials provides a measure of inhibitory control.

DCCS (Dimensional Change Card Sorting)

This task is a measure of cognitive flexibility, also known as task switching or set shifting. The children were instructed to match a centrally presented test stimulus to one of two lateralized target stimuli either by shape or by color with touching the matching target stimulus. After sorting test stimuli according to one dimension either by color or shape (pre-switch block), which was counterbalanced, sorting dimension was switched (switch block). If the children succeeded in both the pre-switch and switch blocks, the mixed block consisting of both color and shape matching tasks was provided. DCCS scores were calculated based on both accuracy and reaction time.

Analysis

One adult participant was excluded from analysis because the participant had explicit knowledge of the probability manipulation as well as the rich quadrant location. Fourteen children failed to complete the task. We first analyzed the data from 49 children who completed all three sessions of the experiment and then ran additional analyses with all participants regardless of completion of the experiment. Trials with reaction times (RTs) beyond 10 seconds were excluded (Jiang et al., 2014; Won & Jiang, 2015) resulting in an elimination 1.97% of trials from children and none from adults. The children's accuracy was 98.44% (*SD* = 1.49%), while the adults'accuracy was 98.33% (*SD* = 1.28%). RTs in the correct trials were analyzed. The RT data from three sessions were collapsed, because all sessions had an identical structure with the same location probability except for the character type. The first five blocks in each session belonged to the training phase and the last one belonged to the testing phase. All statistical analyses were conducted in JASP 0.12.2 (JASP Team, 2020).

Results

The Acquisition of LPL in the Training

Phase

We first investigated the effect of age group on the acquisition of LPL using a mixed factor ANOVA on the participants' RTs during the training phase. The typical LPL would be presented as the facilitation of target detection when the target appears at a rich quadrant compared to the sparse quadrants. For each age group, the means and standard deviations of response times (RTs) between the rich and sparse quadrants were presented in table 1.

The ANOVA model included probability (rich, sparse) and session (1 - 3) as within-subject factors and age group (5 - 6-year-olds, 7 - 9-year-olds, adults) as a between-subjects factor. Simple main effects of probability, $F(1, 68) = 131.290$, $p < .001$, $\eta_p^2 = .659$, and age group, $F(2, 68) = 88.632$, $p < .001$, $\eta_p^2 = .723$, were significant. That is, the RTs in the rich condition were significantly faster than the RTs in the sparse condition, indicating the acquisition of a spatial bias toward the frequent target location (see Figure 2a). The age group effect showed a linear trend, $\beta = -1.540$, $t(68) = -13.290$, $p < .001$, indicating that overall RTs decreased as the participants' age increased. Meanwhile, the main effect of session was not significant, $F(2, 136) = 2.929$, $p = .057$, $\eta_p^2 = .041$. The interaction effect between probability and session was significant with the Greenhouse-Geisser correction, $F(1.579, 107.360) = 17.258$, $p < .001$, $\eta_p^2 = .202$, indicating that the extent of acquired spatial bias significantly changed over the sessions. However, any other interaction effect related to age groups was not significant: probability × age interaction, $F(2, 68) = 2.386$, $p = .100$, $\eta_p^2 = .066$; session× age interaction, $F(4, 136) = 1.801$, $p = .132$, $\eta_p^2 =.050$; probability × age × session interaction, $F(3.158, 107.360) = .656$, $p = .588$, $\eta_p^2 = .019$. That is, neither the acquisition of spatial bias nor the pace of bias acquisition differed across the age groups.

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Table 1. Descriptive statistics for the response times (in seconds) of each session and trial type by age group

	Training		Testing	
	Rich	Sparse	Rich	Sparse
5-6-year-olds (n=26)	3.551(.720)	4.022(.629)	3.459(.830)	3.872(.546)
7-9-year-olds (n=23)	2.693(.579)	3.223(.653)	2.767(.667)	3.162(.605)
Adults (n=22)	1.580(.219)	1.903(.248)	1.593(.266)	1.872(.260)

Note. the means and standard deviations in parenthesis of response times

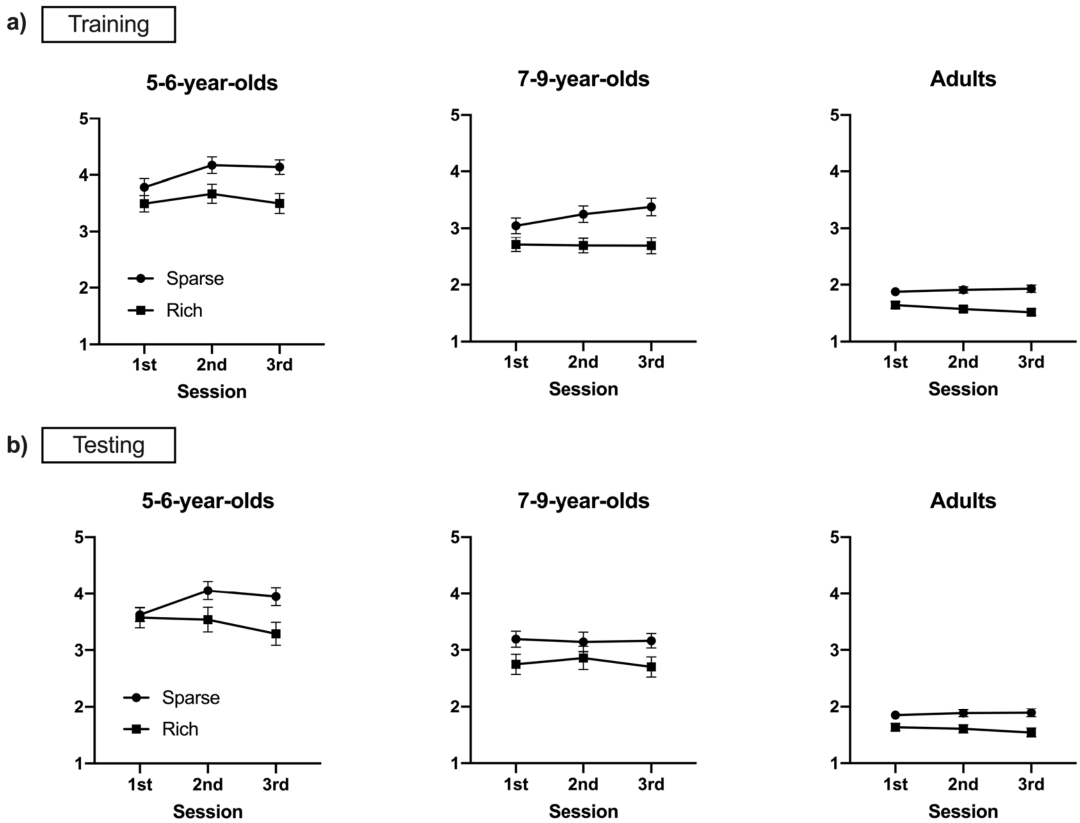

Figure 2. The results of the experiments. a) RTs in the training phase by sessions and by age groups. The error bars indicate standard error of mean. b) RTs in the testing phase by sessions and by age groups. The error bars indicate standard error of mean.

conventional ANOVA do not access evidence for or against the null hypothesis. To quantify the evidence for and against the presence of the age-related interaction effect, we submitted the RTs to a Bayesian mixed factor ANOVA with probability condition, session number, and age groups. Examination of the Q-Q plots suggested that the assumption of normality was not violated. The model including main effects (probability, session, and age group) and a probability × session interaction was most supported by the data, whereas adding the probability by age group interaction decreased the degree of this support by a factor of 1.0/0.662 = 1.51. These results indicate that the data provided decisive evidence for the acquisition of LPL early in development, but the evidence against age-related differences in LPL was inconsequential.

The Persistence of LPL in the Testing Phase

In the testing phase, contrary to the training phase, a target appeared in all four quadrants with equal probability. Accordingly, the spatial bias in the testing phase cannot be explained by short term inter-trial response priming. Instead, spatial bias toward the rich quadrant would indicate that the participants successfully acquired long-term statistical knowledge. A mixed factor ANOVA with probability (rich, sparse) and session (1-3) as within-subject factors and age group (5-6-year-olds, 7-9-year-olds, adults) as a between-subjects factor was conducted to explore the existence of long-term statistical knowledge across different age groups (Figure 2b). The main effects of probability and age group were significant, $F(1, 68) = 37.607$, $p < .001$, $\eta_p^2 = .356$, $F(2, 68) = 82.497$, $p < .001$, $\eta_p^2 = .708$, respectively. These results implied that the LPL persisted even after the probability of target distribution was equal across all quadrants, but the overall RTs differed by age group. As in the training, the main effect of session was not significant, $F(2, 136) = .780$, $p = .461$, $\eta_p^2 = .011$, but the interaction effect between probability and session was significant, $F(2, 136) = 3.087$, $p = .049$, $\eta_p^2 = .043$. Any other interaction effect related to age groups was not significant: probability × age interaction, $F(2, 68) = .470$, $p = .627$, $\eta_p^2 = .014$; session× age interaction, $F(4, 136) = .331$, $p = .856$, $\eta_p^2 = .010$; probability × age × session interaction, $F(4, 107.360) = .656$, $p = .588$, $\eta_p^2 = .019$. The results from the testing phase demonstrated that controlling for inter-trial repetitions, the learned spatial bias still preserved regardless of the participant's age, and the bias that learned during searching for a specific item could be transferred to searching for a different item.

A Bayesian mixed factor ANOVA resulted in a probability and age main effects only model as the best-representing model of the data compared to the null model, $BF_{10} = 4.078 \times 10^{23}$, indicating decisive evidence in favor of the persistence of LPL and age-related decrease in overall RTs. The addition of probability × age group interaction decreased the extent of this support by a factor of 1/.076 = 13.157. Adding the main effect of session order with the probability × age group interaction dropped the BF by 1/.023 = 43.478 factor when compared to the best model. These results showed positive evidence for developmental invariance in the persistence of LPL. Thus, the results of the Bayesian ANOVAs from both the training and testing phases exhibited decisive evidence of the robust acquisition and persistence of LPL across different age groups.

To eradicate the effect of different baseline

RTs across participants, we generated a standardized cueing index. The standardized cueing index could be a better measure than the raw RT difference between the sparse and rich conditions because it takes into account overall RT differences when determining the magnitude of LPL. The standardized cueing index (Ci) was calculated based on averaged RTs in each block with the following equation:

$$Ci = \frac{(RTs\ of\ sparse\ condition - RTs\ of\ rich\ condition)}{(RTs\ of\ sparse\ condition + RTs\ of\ rich\ condition)}$$

A zero value of the cueing index indicates the absence of spatial bias either toward the rich or sparse target locations. A larger cueing index indicates a greater spatial bias toward the frequent target location.

A mixed factor ANOVA was applied to cueing indices in the testing phase with the order of session (1-3) as a within-subject factor and age group as a between-subjects factor. The effect of the session order was significant, $F(1.763, 119.880) = 21.266$, $p < .001$, $\eta_p^2 = .238$, with its linear trend, $\beta = .038$, $t(136) = 6.494$, $p < .001$. Other effects and interaction were not significant. This result indicates that the extent of the spatial bias increased as sessions progressed regardless of the target item identity, however the magnitude and increasing trend of the bias did not differ across different age groups, $F(2, 68) = 1.472$, $p = .237$, $\eta_p^2 = .026$; $F(3.526, 119.880) = 21.266$, $p < .001$, $\eta_p^2 = .238$, respectively.

As was done in the analyses of raw RT difference above, we assessed the evidence for and against the presence of the age-related effect on the magnitude of LPL using a Bayesian mixed factor ANOVA with the order of session and age groups as factors. The session order main effect only model was best supported by the data compared to the null model, $BF_{10} = 2.132 \times 10^6$, which indicates decisive evidence for an increase in the magnitude of LPL as learning progressed. However, the addition of either age main effect or session × age group interaction dropped the degree of this support by a factor of 1/.434 = 2.304 and 1/.014 = 72.428, respectively. Although the results showed strong evidence against age-related differences in the learning effect of LPL, the evidence against age-related difference in the magnitude of LPL was inconsequential ($BF_{10} = 2.304$). Thus, we considered the inclusion Bayes factor for each of the model's predictor based on all possible models simultaneously and observed decisive evidence for the inclusion of the order of session, $BF = 1.513 \times 10^6$, but neither for the inclusion of age group, $BF = .314$ nor for the inclusion of the session order × age group interaction, $BF = .041$. The overall results demonstrated that the children and adults gradually acquired a spatial bias toward the rich quadrant, and they accumulated their learning experiences regardless of identity change in target items between sessions. This learned spatial bias was preserved even when the targets were evenly distributed in the searching space, and its magnitude was constant across age groups. These results implied that the acquisition and persistence of LPL could be developmentally invariant, unlike explicit attention learning.

The Effect of Development-dependent Factors on the Children's LPL

Even though the group analyses of LPL resulted in insignificant age-related effects, there was substantial variability in children's LPL, indicating that there may have been individual differences in their LPL. Hence, we evaluated whether development-dependent learning factors (on top of chronological age) such as executive function and memory would affect children's LPL. It has been known that the form of difference scores (i.e., differences in response times between conditions, such as congruent and incongruent conditions of a Stroop task) could increase measurement errors and decrease reliability (Cohen & Cohen,1983; Friedman & Miyake, 2004; Hedge, Powel, & Sumner, 2018), resulting in low correlations between the difference scores and other individual ability scores. Therefore, instead of using the cueing index as the measure of LPL, we used the residual of RTs in the rich condition after regressing out RTs in the sparse condition, reasoning that the residual should be a combination of probability cueing effect and measurement error (Cronbach & Furby, 1970; Friedman & Miyake, 2004). RTs in the sparse condition predicted 55.2% of the variance in RTs in the rich condition. The residual variance (54%) was significantly greater than zero, $t(48) = 3.789$, $p < .001$, Cohen's $d = .541$, suggesting RTs in the rich condition contained enough variance not attributable to baseline response latency. The reliability estimate of the residualized difference scores was reasonable, Cronbach's $\alpha = .616$, 95% confidence interval = [0.320, 0.780]. Descriptive statistics for NIH toolbox measures, the residualized difference score of LPL, and their correlations are presented in Table 2. Since the toolbox tasks were given after performing the search task, some children refused to participate in more than two toolbox tasks because of fatigue. Among 49 children who completed all sessions of the search task, 29 children also finished all toolbox tasks, but 20 children did not complete more than one tool box task.

We first verified that there were age-related changes in children's executive function by regressing each task scores on

Table 2. Descriptive Statistics and Correlations for the Variables of Interest

	Mean (SD)	1	2	3	4	5	6	7
1. PSM (long-term memory)	99.161 (22.18)	–						
2. LSWM (working memory)	89.102 (19.467)	.099 (n=31)	–					
3. DCCS (set switching)	84.094 (27.33)	.145 (n=30)	.463* (n=30)	–				
4. Flanker (inhibitory control)	93.082 (19.727)	.047 (n=31)	.716*** (n=48)	.078 (n=30)	–			
5. Cueing Index (LPL)	.068 (.086)	.094 (n=32)	.002 (n=48)	-.304 (n=31)	.145 (n=48)	–		
6. Residualized Diff. (LPL)	.008 (.556)	-.109 (n=32)	.015 (n=48)	.317 (n=31)	-.095 (n=48)	-.973*** (n=71)	–	–
7. Age	6.998 (1.153)	.031 (n=32)	.309* (n=48)	.254 (n=31)	.364* (n=31)	.034 (n=48)	.058 (n=71)	–

Note: PSM, Picture Sequence Memory; LSWM, List Sorting Working Memory; DCCS, Dimensional Change Card Sorting Test; LPL, location probability learning
* $p < .05$, ** $p < .01$, *** $p < .001$

their age. Children's age was a significant predictor for their working memory (LSWM), β = 5.220, $F(1, 47)$ = 4.842, p = .033, and inhibitory control (Flanker task), β = 6.226, $F(1, 47)$ = 7.024, p = .011, but not for cognitive flexibility (DCCS) scores, β = 3.460, $F(1, 30)$ = 2.000, p = .168, and episodic memory retrieval (PSM), β = .549, $F(1, 31)$ = 0.029, p = .866. Children's age predicted neither the change in the cueing index nor that in the residualized difference score as shown in Figure 3: β =.003, $F(1, 47)$ = .055, p = .816; β = -.028, $F(1, 47)$ = .157, p = .693, respectively.

Then, we carried out a Bayesian multiple regression analysis for the children's residualized difference scores in the testing phase with standardized scores of LSWM, PSM, Flanker, and DCCS tests, and their age as predictors, so as to address whether these individual differences in executive function affected children's LPL. An uninformed uniform prior, P(M) = .031 was set for each of all possible models. However, no possible regression model resulted in considerable evidence against the null model, as shown in Table 3 (i.e., Residualized Difference Models). The 95% of credible

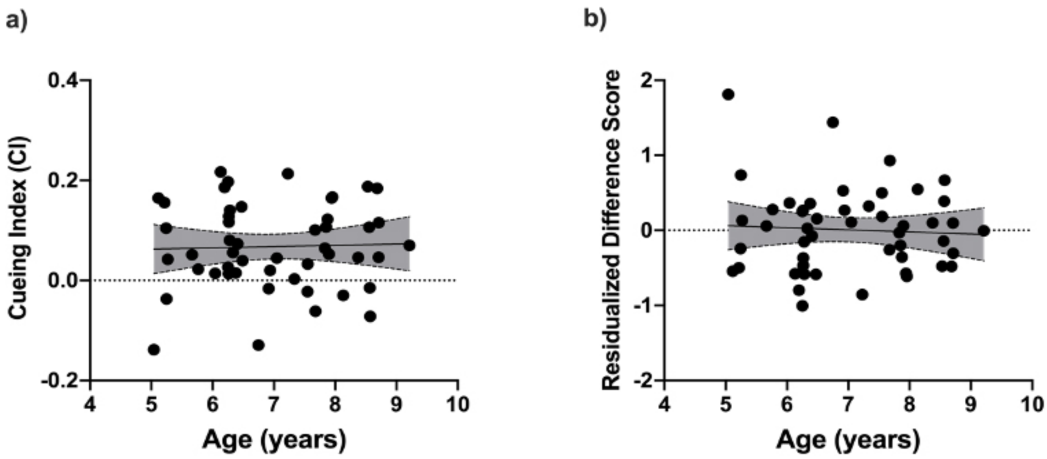

Figure 3. The nonsignificant age effect on the magnitude of children's LPL. a) Regression line between children's age and cueing index in the testing phase. b) Regression line between children's age and residualized difference score in the testing phase. Individual circles match to the individual data points. Shaded area reflects 95%confidence interval.

Table 3. Subsets of 4 best Bayesian Linear Regression Models for Predicting Variables of Children's Visual Search Performances

Models	P(M)	P(M|data)	BF_M	BF_{10}	R^2
Residualized Difference Models					
Null model	.031	.047	1.543	1.000	.000
DCCS	.031	.083	2.800	1.747	.142
LWSM	.031	.082	2.781	1.737	.141
LWSM + flanker	.031	.065	2.146	1.365	.195
LWSM + DCCS	.031	.063	2.069	1.320	.192
Overall RT Models					
Null model	.031	.007	.2173	1.000	.000
LSWM + Age	.031	.148	5.365	21.267	.381
Age	.031	.135	4.854	19.517	.308
LSWM + DCCS + Age	.031	.097	3.348	14.050	.416
LSWM + DCCS + flanker + Age	.031	.092	3.133	13.231	.464

Note: P(M) = prior model probability; P(M|data) = posterior model probability; BF_M = change from prior model odds to posterior model odds; BF_{10} = Bayes factor for each model against the null model intervals of all the covariates included in the analysis contained zero inside: Age, [-0.067, 0.089]; PSM, [-0.007, 0.002]; LSWM, [-4.284, 0.017]; DCCS, [-0.002, 0.013]; flanker, [-0.011, 0.004]. These results suggest that the magnitude of LPL was not only developmentally invariant but also independent of individual differences in executive function and memory.

To account for the possibility that the search task itself might not be sensitive enough to catch age-related or individual differences for some reason, we applied similar Bayesian multiple regression models to the overall RTs. The overall RT model including working memory and children's age provided strong evidence against the null model, $BF_{10} = 21.267$, and other models including the set switching and inhibition as well as working memory and age also showed strong evidence against the null model (see Overall RT Models in Table 3). Thus, although the search task and cueing indices were sensitive enough to detect age-related or individual differences, the children's long-term LPL during testing was not correlated with their development-dependent learning factors. These results confirmed the notion that LPL is distinguishable from the explicit learning mechanism, in that LPL is developmentally invariant and independent from development -dependent learning factors.

Discussion

The aims of the current investigation were 1) to determine when and how children acquire adult-like LPL and 2) to examine whether the acquisition of LPL is affected by development-dependent learning factors. To our knowledge, this is the first empirical investigation of the developmental nature of LPL making direct comparisons to adults' LPL. With age-appropriate stimuli and response methods, children aged 5-9 years successfully learned the statistical regularity of the target location and used this knowledge to guide their spatial attention. The extent of their learned spatial bias in the testing phase was also equivalent to adults' learning. Furthermore, the children's LPL was independent of their executive functions.

Our results have several implications for understanding the nature of LPL. First, our data provide evidence that children can learn the probability of target locations and use it to guide their spatial attention without explicit awareness. The magnitude of their learned spatial bias was comparable to adults' learning, suggesting the presence of a highly functioning implicit spatial attention mechanism early in development. This is consistent with findings showing early mature implicit learning (Amso & Davidow, 2012; Aslin, 2017; Finn et al., 2016; Thomas et al., 2004). In light of previous findings on older adults' spared LPL (Jiang, 2018; Twedell et al., 2017), the current investigation added evidence to demonstrate a developmental trajectory of stable LPL from young childhood to late adulthood.

Second, our results revealed the independence of the children's LPL from development-dependent learning factors. While the children's age, working memory capacity, and inhibitory control successfully predicted overall search efficiency, the magnitude of LPL was not related to these factors. Independence of general fluid intelligence has been considered as a significant feature of implicit learning (Dienes & Berry, 1997) because implicit learning is believed to be dependent on the basal ganglia memory system separately from the prefrontal cortex-and medial temporal lobe-dependent memory system (Janacsek & Nemeth, 2013; Poldrack et al., 2001). Independence of children's LPL from working memory corresponds to the previous study showing that a secondary working memory task did not interfere with adults' LPL (Won & Jiang, 2015). Parkinson's patients, who often have impaired working memory and executive function, also showed unimpaired LPL (Sisk et al., 2018).

Different developmental trajectory between implicit and explicit learning can be found in other cognitive tasks. For example, young children showed adult-like performance in an implicit memory test such as perceptual priming (Carroll, Byrne, & Kirsner, 1985). Also, children's performance was comparable to adults in other implicit cognitive tasks such as artificial grammar learning or probabilistic classification (Finn et al., 2015). However, explicit memory tests revealed age group differences (Billingsley, Smith, & McAndrews, 2002). These results show that implicit and explicit learning may rely on different neural circuits. Indeed, a significant LPL effect was observed in patients with parietal damages, suggesting that brain regions involved in goal-driven attention is not essential for LPL (Geng & Behrmann, 2002; Jiang, 2018). Overall, our results confirm that the underlying mechanism serving LPL is qualitatively different from that of explicit learning.

It is well-known that goal-driven attention control undergoes a great deal of developmental change that extends over a prolonged period of development (e.g., Lookadoo, Yang, & Merrill, 2017; Rueda et al., 2004). Rather, our data demonstrated stable LPL from early childhood to early adulthood, which has distinguishable characteristics from goal-driven attention, such as being implicit, inflexible, resource-independent, and task-specific. LPL has been proposed as a distinctive form of procedural /habitual attention acquired through reinforcement learning (Jiang et al., 2013), compensating for a decline, and protracted development of goal-driven attention. As people may guide their attention habitually rather than declaratively under distraction, time pressure, and limited task ability, young children experiencing more difficulty in suppressing singleton distractors may overcome this interference by deploying habitual attention control when distractors appear in a repeated display (Goschy et al., 2014; Wang, Samara, & Theeuwes, 2019).

What precisely do children learn from environmental regularity? Does repeated target location guide children's spatial attention to important locations during a search, or does it speed up planning and execution of response after finding a target by inter-trial response repetition? Our data showed that RT facilitation in the rich quadrant remained persistent even when the target location was evenly distributed in the search space. Without response repetition, the children still responded faster to the target in a rich location. Previous adult studies revealed that the first saccadic eye movement (within 200 ms after stimuli onset) was directed toward the rich region (Jiang, Won, & Swallow, 2014) and LPL occurred even when the participants were not allowed to move their eyes (Jiang et al., 2014). Similar to adults, it is likely that children in the current study learned spatial attention bias instead of response repetition or oculomotor routine. However, it is still possible that children learned a routine of dexterous hand movements instead of spatial attention bias because our search task directly associated finger tapping response with target selection, unlike previous adult studies. Further studies will be necessary to fully dissociate spatial attentional bias from motor learning.

To summarize, this study suggests that location probability learning ability appears early in childhood and is maintained at a constant level across development, as suggested by the developmental invariance approach of implicit learning. The current study contributes to making progress toward elucidating the developmental origin of the habitual attention system.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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시각탐색 과제 수행 중에 목표 자극이 빈번하게 출현하는 위치로 시각적 주의를 빠르게 이동하는 현상을 위치확률단서학습(Location probability learning, LPL)이라 한다. 위치확률단서학습의 경험적 증거는 대부분 성인집단에서만 확인되었기 때문에, 위치확률단서학습이 처음으로 가능한 연령이 언제인지 그리고 아동의 연령이나 일반적인 인지적 능력이 발달함에 따라 변화하는지에 대한 메커니즘 측면의 이해가 부족한 상황이다. 본 연구에서는 5-9세 사이의 학령전기와 학령기아동 집단과 성인집단의 시각탐색 과제 수행 중에 목표자극의 출현위치 확률을 조작하여 1) 아동집단에게서도 위치확률단서학습이 가능한지, 2) 확률학습의 크기나 습득양상이 성인집단과 다른지, 그리고 3) 학습과 관련한 영역일반적 인지능력의 변화에 의해 위치확률단서 학습이 영향을 받는지를 탐색하였다. 모든 연령의 아동에게서 위치확률단서학습이 발생하였고, 그 크기와 습득양상에 있어서도 성인집단과 다르지 않았다. 게다가 작업기억이나 억제통제와 같은 인지통제능력의 변화는 위치확률단서학습과 상관이 없는 것으로 나타났다. 즉 위치확률단서학습은 학령전기부터 성인기까지 발달적 불변성을 보여주어, 아동기 초기에 발달적 변화가 극명한 목표주의의 발달과는 다른 발달궤적을 가진다는 주의발달의 이중경로 이론을 지지한다.

주요어 : 위치확률단서학습, 통계학습, 암묵학습, 아동발달