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Infant walking experience is related to the development of selective attention

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ABSTRACT

Previous studies have shown that the way in which infants perceive and explore the world changes as they transition from crawling to walking. Infant walking onset generally precedes advances in cognitive development such as accelerated language growth. However, the underlying mechanism explaining this association between walking experience and cognition is largely unknown. Selective attention is a key factor underlying learning across multiple domains. We propose that the altered visual input that infants obtain as they transition to walking relates to selective attention development and that advances in selective attention may potentially explain previously reported advances in other cognitive domains. As a first step in testing this hypothesis, we investigated how walking experience relates to selective attention. In Study 1, performance of 14-month-old crawlers, novice walkers, and expert walkers was compared on a visual search eye-tracking task (N = 47), including feature and conjunction (effortful) items. Walkers outperformed crawlers on the task in general, and effortful search was enhanced in expert walkers as compared with novice walkers, after controlling for crawling onset and general developmental differences occurring before walking onset. In Study 2, earlier walking onset was related to better visual search performance in 2-year-olds (N = 913). The association appeared to be due to the difference between the 10% latest walkers and the early/average walkers.

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Taken together, the results of these studies show that walking experience relates to advances in selective attention. This association shows a specific timing in development; it is mainly seen relatively close to the age of walking onset.

Introduction

According to the ecological approach to developmental psychology (e.g., Adolph, 2019; Gibson, 1988), infant self-locomotion plays an important role in cognitive development. In particular, attainment of self-locomotion milestones, such as crawling and walking, affects the way in which infants interact with their environment, providing them with new opportunities for exploration and learning. Put differently, learning to crawl or walk fundamentally changes children's affordances (Gibson, 1988; Thelen, 2000). The term *affordances* is central to the ecological approach and refers to action possibilities that are dependent on the characteristics of both the acting organism and the environment (Gibson, 1979). A number of studies have shown that self-locomotion onset and experience are related to advances in a range of other developmental domains, including vocabulary learning, memory, and understanding of others' intentional actions during infancy (Brandone, 2015; Herbert, Gross, & Hayne, 2007; Oudgenoeg-Paz, Volman, & Leseman, 2012; Walle & Campos, 2014). However, little is known about the precise characteristics of these relations. What is the underlying mechanism through which the achievement of infant self-locomotion milestones relates to cognitive development? The aim of the current study was to contribute to this topic by investigating how self-locomotion experience during infancy affects the development of selective attention, a crucial skill needed for learning across multiple domains (e.g., Stevens & Bavelier, 2012; Yu & Smith, 2011).

Although the majority of studies have focused on the transition from pre-self-locomotion to self-locomotion (generally crawling), showing robust links with, for example, memory development (e.g., Herbert et al., 2007; Kermoian & Campos, 1988; for a review, see Campos et al., 2000), a few studies have shown that walking experience relates to cognitive advances in a similar fashion (Clearfield, 2004; Oudgenoeg-Paz et al., 2012; Walle & Campos, 2014). An important question is whether such effects can indeed be ascribed to self-locomotion experience or whether general maturational differences between children account for both individual differences in self-locomotion onset and differences in other developmental domains (the general maturational factor as third variable). That is, is there a *causal* relation between infant self-locomotion and cognitive development? To address this issue, Kermoian and Campos (1988) compared performance on a working memory task among three groups of 8.5-month-old infants: infants who had no self-locomotion experience, infants who had no self-locomotion experience except for walker-assisted experience, and infants with crawling experience. The crawlers and walker-assisted groups obtained similar scores on working memory that were significantly better than those of the infants without self-locomotion experience. These findings thus point to a true effect of self-locomotion experience on cognitive development. Similarly, two longitudinal studies showed that walking onset was followed by enhanced growth in vocabulary (Oudgenoeg-Paz et al., 2012; Walle & Campos, 2014). Thus, there is at least some evidence that infant walking experience may propel cognitive development.

A number of studies provide important information on the mechanisms underlying the associations between walking experience and cognitive development. First, Karasik, Tamis-Lemonda, and Adolph (2014) showed that walking changes the way in which infants share objects with their caregivers compared with crawling, and this change elicits different forms of verbal responses from caregivers. Specifically, walking infants share more objects while locomoting, and these so-called "moving bids" elicit more action directives from caregivers. The authors proposed that this may subsequently enhance language development. Second, in a study by Walle (2016), infants more often initiated joint engagement with their caregivers after 2 to 4 weeks of walking experience and also were more likely to follow parent-initiated joint engagement. The infants' following of parent-initiated joint engagement predicted receptive vocabulary development, indicating that changes in social interaction may mediate between infant walking experience and language development. However, the relation between walking experience and receptive vocabulary remained significant even after controlling for infants' following of parent-initiated joint engagement (Walle, 2016), suggesting that there are also other factors at play such as other aspects of social interactions (e.g., parent language input; Walle & Campos, 2014).

Whereas the studies described above show that social interaction while locomoting is a candidate mechanism through which walking and language development are related, a third longitudinal study by Oudgenoeg-Paz, Leseman, and Volman (2015) showed that even without the active involvement of their caregivers, children with more walking experience (i.e., children with earlier walking onset) engaged in more exploration of spatial relations in their environment while they were locomoting as compared with children with less walking experience. Exploration behavior partially explained the relation between walking onset and spatial language and spatial cognition during toddlerhood. Thus, advanced exploration opportunities form another candidate mechanism through which infant walking experience may relate to cognitive advances during infancy.

Finally, and relatedly, Campos and colleagues (2000) proposed that the association between self-locomotion experience and cognitive task performance may perhaps be due to improved attentional discrimination in infants with more self-locomotion experience. Although recent studies have shown that infant walking during exploration is generally not goal directed in nature (Cole, Robinson, & Adolph, 2016; Hoch, Rachwani, & Adolph, 2019), the visual input infants receive when they are moving, whether goal directed or not, seems to be markedly different for crawlers compared with walkers (e.g., Clearfield, 2011; Karasik, Tamis-Lemonda, & Adolph, 2011; Kretch, Franchak, & Adolph, 2014). For example, Kretch et al. (2014) studied 13-month-old crawlers' and walkers' visual experiences as these infants moved along a walkway toward their caregivers and showed that the highest point visible was twice as high for walkers compared with crawlers. In addition, while locomoting, walkers looked at their caregivers more often than crawlers, whereas crawlers looked at the floor more often. Other studies showed that walkers tend to travel longer distances compared with crawlers and more frequently show objects to their caregivers while on the move (Adolph et al., 2012; Karasik et al., 2014). A recent head-mounted eye-tracking study showed that the distance at which infants initiate eye contact with their caregivers in the home increased as a function of walking experience. At longer distances, the average number of objects between infants and caregivers increased, providing a more cluttered view from the infants' perspective for walkers (Yamamoto, Sato, & Itakura, 2020). Identifying and maintaining focus on a "target" object for joint engagement likely requires more effort in such complex versus less complex scenes due to the number of other (potentially distracting) stimuli in view. Moreover, as walkers explore the environment more while moving, (experienced) walkers need to actively select the properties of the object and the environment they focus on in order to combine them into a new (more complex) action such as a moving bid or kicking a ball through a hoop (Karasik et al., 2014; Oudgenoeg-Paz et al., 2015). Thus, the empirical evidence to date suggests that attentional demands faced by walkers may be greater than those faced by crawlers. However, it is currently unknown whether these increased attentional demands lead to enhanced development of attention as a function of walking experience.

Thus, previous work has shown that walking experience relates to advances in various cognitive domains such as language development (e.g., Oudgenoeg-Paz et al., 2012; Walle & Campos, 2014). Candidate variables mediating this association involve changes in social interaction (Karasik et al., 2014; Walle, 2016) and exploration behavior (Oudgenoeg-Paz et al., 2015). Further work is needed to test how such mechanisms may operate precisely (cf. Walle, 2016). A potentially important, yet understudied, variable in this context is selective attention.

Selective attention is the ability to focus on relevant information while ignoring distractors (Van der Stigchel et al., 2009). A frequently used paradigm to assess selective attention throughout development is the visual search task (Hommel, Li, & Li, 2004). In a visual search task, the participant searches for a "target" element, which is presented together with non-target elements, generally termed "distractors." A distinction is often made between feature search and conjunction search trials (Treisman & Gelade, 1980; Van der Stigchel et al., 2009). In *feature search trials,* the target is different from the distractors by a unique feature (e.g., a red apple among green apples), which results in a pop-out of the target amid the distractors. Specifically, the unique target automatically captures attention, as indicated by the observation that when the number of distractors is increased, the reaction time to find the target is not affected (also known as *parallel* search). In *conjunction search trials,* the target is different from the distractors because it has a unique combination of features, each of which occurs in the distractors as well (e.g., a red apple among green apples and red bananas). In contrast to parallel search, conjunction search trials require participants to serially shift visual attention to each stimulus in the search array in order to detect the target. Therefore, when the number of distractors is increased, the reaction time to find the target also increases, which has been taken as an indication that effortful serial search is required to locate the target.

Early individual differences in selective attention predict cognitive development (see Hendry, Johnson, & Holmboe, 2019). For example, infant selective attention plays a key role in word learning (Yu & Smith, 2011), and individual differences in toddler selective attention predict executive function (Veer, Luyten, Mulder, Van Tuijl, & Sleegers, 2017). The visual search paradigm can be used to measure selective attention already during the first years of life. In fact, the distinction between parallel and effortful serial search has been observed consistently across development, from infancy through adulthood (Donnelly et al., 2007; Gerhardstein & Rovee-Collier, 2002). For example, 3-month-old infants have been reported to already show pop-out effects in visual search similar to adults (Adler & Orprecio, 2006), and response patterns in children as young as 1 to 3 years of age have been shown to be indicative of effortful parallel search on conjunction trials on a visual search task (Gerhardstein & Rovee-Collier, 2002). Furthermore, in addition to the feature versus conjunction distinction, the level of similarity between targets and distractors is a key factor determining the level of effort required to execute a selective attention visual search task in young children (Scerif, Cornish, Wilding, Driver, & Karmiloff-Smith, 2004). Thus, these studies suggest that effortful visual search can be assessed in young children through measuring responses both on conjunction trials and on trials in which the target and distractors are relatively similar even though the target may differ from the distractors by a unique feature.

The current investigation

Walking infants travel longer distances than crawling infants (Adolph et al., 2012), and the view that infants have during interaction with their caregivers is typically more cluttered at these longer distances (Yamamoto et al., 2020). Moreover, the ability to locomote in an upright position enables children to combine actions and thus act on complex affordances, requiring focus on and integration of multiple relevant object properties, likely placing greater demands on visual selective attention in walking versus crawling infants. In addition, joint engagement with a caregiver has been reported to increase with walking experience (Walle, 2016), and joint engagement with a caregiver lengthens duration of selective attention in infants (Yu & Smith, 2017). Therefore, we hypothesized that walking experience would relate to effortful visual selective attention. Selective attention is a key factor involved in a range of other cognitive domains such as executive function (Veer et al., 2017) and word learning (Yu & Smith, 2011) and thus may be a mediating variable in the association between walking experience and cognitive functions. In the current study, we aimed to take a first step in testing these associations by investigating whether walking experience relates to selective attention development during the first years of life.

Two studies were conducted to assess whether walking experience relates to selective attention during early childhood. In Study 1, we compared the performance of 14-month-old crawlers, novice walkers, and expert walkers on a selective attention eye-tracking task with feature and conjunction items. In Study 2, we investigated, in a different group of children, whether there was an association between walking onset during infancy and selective attention at toddler age using behavioral data from a visual search task in which the target was relatively similar to the distractors.

Study 1

Using an age-held-constant design, performance of 14-month-old crawlers, novice walkers, and expert walkers was compared on a selective attention eye-tracking task. In Study 1, we hypothesized that walking experience would relate to selective attention task performance and, in particular, that walking experience would be positively related to performance on the conjunction trials, but not on the feature trials, of the selective attention task. The attentional demands faced by walkers in everyday life may be higher than those faced by crawlers (cf. Yamamoto et al., 2020), which provides walkers with more experience in making an effortful distinction between goal objects and distracting objects and between goal properties and distracting properties, as in the conjunction trials. During feature trials, the target pops out from among the distractors, and thus finding the target requires little effort. As such, no effortful attention is required for feature trials, and therefore crawlers' and walkers' performance is not expected to differ. Previous work has shown that the effect of walking on acquisition in other domains (e.g., language) occurs after 2 to 4 weeks of walking experience (Walle & Campos, 2014). Thus, we hypothesized that the number of weeks of walking experience within the group of walkers would be a factor in selective attention development, such that expert walkers would outperform novice walkers on the conjunction trials but not on the feature trials. Finally, we explored whether any associations between infant walking experience and selective attention at 14 months of age were due to initial developmental differences seen prior to walking onset at 10 months or the number of weeks since crawling onset at 14 months or were specific to walking experience.

Method

Sample

Parents and infants were recruited through a local community mailing in a city in the Netherlands. Infants were recruited before 10 months of age because the majority of infants do not walk yet at this age in the Netherlands (Van Baar, Steenis, Verhoeven, & Hessen, 2014). A total of 77 infants participated in the study. For the current study, a subsample of infants who were either crawlers, novice walkers, or expert walkers at 14 months was selected, as further outlined below. The age of 14 months was chosen for our selective attention assessment because this is around the average age at which infants in the Netherlands typically learn to walk (Van der Meulen, Ruiter, Spelberg, & Smrkovský, 2004; see also the current Study 2).

Biographical information of the groups is shown in Table 1 for infants with test data on selective attention (as described further below). Parental education was coded on a 4-point scale ranging from primary school (1) to higher vocational education or university (4) and averaged across both parents. Ethnicity was coded into three groups: Dutch, Western non-Dutch (where at least one parent was born in a Western country other than the Netherlands), and non-Western non-Dutch (where at least one parent was born in a non-Western country). There were no differences among the three groups in terms of the gender distribution, $\chi^2(2) = 0.498$, $p = .780$, ethnicity (Fisher's exact $p = .389$), parental education, $F(2, 41) = 1.310$, $p = .281$, or assessment age, $F(2, 44) = 1.503$, $p = .234$. None of the infants in either of the groups was reported to have been born preterm (i.e., gestational age < 37 weeks), blind, or deaf or to have suffered from brain damage, a chronic disease, or physical disability.

Classification of infants as belonging to the crawler, novice walker, and expert walker groups

The Alberta Infant Motor Scale (AIMS; Piper & Darrah, 1994) and parental reports were used to classify infants into the groups of crawlers, novice walkers, and expert walkers. Before describing the selection of the groups, these different sources of information are described in turn.

Alberta Infant Motor Scale. Research assistants (RAs) conducted the AIMS (Piper & Darrah, 1994) as part of the lab visit following training by an experienced pediatric physiotherapist. The AIMS is an assessment tool designed to track motor development in infants aged 0 to 18 months across four scales: prone, supine, sitting, and standing. The prone and standing scales include items about crawl-

Table 1
Background characteristics of crawlers, novice walkers, and expert walkers for infants with valid selective attention test data

	Full sample (*N* = 47)	Crawlers (*n* = 14)	Novice walkers (*n* = 16)	Expert walkers (*n* = 17)
		n/total *N* (%)		
Gender				
Boys	27/47 (57%)	7/14 (50%)	10/16 (62%)	10/17 (59%)
Girls	20/47 (43%)	7/14 (50%)	6/16 (38%)	7/17 (41%)
Child ethnicity				
Dutch	39/44 (89%)	13/14 (93%)	13/16 (81%)	13/14 (93%)
Western, non-Dutch	2/44 (5%)	0/14 (0%)	1/16 (6%)	1/14 (7%)
Non-Western	3/44 (7%)	1/14 (7%)	2/16 (13%)	0/14 (0%)
		M (*SD;* range)		
Parental education	3.9 (0.2; 3.0–4.0)	3.8 (0.2; 3.5–4.0)	3.9 (0.3; 3.0–4.0)	4.0 (0.1; 3.5–4.0)
Age in months at lab visit	14.6 (0.2; 14.2–15.5)	14.5 (0.1; 14.3–14.9)	14.6 (0.3; 14.2–15.5)	14.7 (0.2; 14.3–15.1)

Note. Three parent questionnaires were missing for the expert walkers.

ing and walking, respectively, and were used in the current study as further outlined below. Full details on the items used and reliability of the AIMS assessment are given in the Appendix.

Parent reports. Parents reported about infants' age of attainment of gross motor milestones in a questionnaire (Bodnarchuk & Eaton, 2004; Dutch translation from Oudgenoeg-Paz et al., 2012). Two items were used to inquire about infants' ability to walk independently: Parents were asked to report when their children were first able to walk short distances (i.e., infants can take at least one step with each foot independently) and longer distances (i.e., independent walking is infants' main mode of self-locomotion). One item was used to assess infants' ability to crawl on hands and knees. Parents were encouraged to use reference material, such as videos, digital photos, or information from the baby clinic, to assist them with their reports. Bodnarchuk and Eaton (2004) showed that parental reports regarding these milestones are valid. Moreover, another study showed that retrospective parent reports administered during toddlerhood provide relatively unbiased data on major motor milestones such as the age at which infants learn to walk independently (Langendonk et al., 2007).

First, infants were classified into crawlers and walkers based on the AIMS assessment. In case parent report data were also available, infants were excluded from either group when this information source conflicted with the AIMS (*n* = 6). In addition, when the AIMS scores were missing, parent report data were used to classify children into the groups of crawlers or walkers (*n* = 3). Second, walking infants were classified into novice and expert walkers based on the number of weeks of walking experience infants had when they came to the lab, as further outlined below.

Crawlers. When infants passed the AIMS item(s) "reciprocal creeping 1" and/or "reciprocal creeping 2" (see Appendix for description), and did not yet pass the items "early stepping" and "walks alone," they were classified as crawlers. The total group of crawlers included 23 infants.

Walkers. When infants passed the AIMS item(s) "early stepping" and/or "walks alone" (see Appendix), they were classified as walkers. The group of *novice walkers* contained infants who had a relatively limited degree of independent walking experience; that is, they were able to walk short distances but had not yet walked long distances for at least 4 weeks. Infants in this group had taken their first independent steps (short distances) on average 5.3 weeks before the lab visit (*SD* = 3.3, range = 0.8–12.5) according to parent report, and they had been walking longer distances independently for an average of 1.5 weeks (*SD* = 1.4, range = 0–4.0 weeks; one infant had missing data on this variable and had walked short distances only 2.9 weeks at the time of the lab visit). The total group of novice walkers included 19 infants. Note that some infants in this group were early steppers, according to the AIMS, and only walked short distances according to parent report; therefore, they might not technically meet the criteria for inclusion in the group of walkers used in some other studies, where a cutoff of being able to walk 3 m without support is usually taken to differentiate walkers from crawlers (Karasik et al., 2011; Walle & Campos, 2014). We opted for the categorization applied here to ensure that the group of crawlers was a group without any independent walking or stepping experience and that such experience could not have affected visual selective attention. However, because all expert walkers in our study engaged in independent walking of longer distances for more than 4 weeks, the division between early and experienced walkers is in line with other work in the field (Walle, 2016).

Parents in the group of *expert walkers* reported that their infants had been able to walk longer distances for more than 4 weeks at the age of the lab visit. These infants had taken their first independent steps (short distances) on average 15.0 weeks before the lab visit (*SD* = 5.2, range = 7.0–28.5) according to parent report and had been walking longer distances independently for an average of 11.6 weeks (*SD* = 5.1, range = 4.2–24.2). The group of expert walkers included 22 infants.

Infants not classified into any of the groups. Of the sample of 77 infants, 13 could not be classified as crawlers or walkers because there was a discrepancy between AIMS scores and parent reports (n = 6), they were not yet able to crawl or walk at 14 months of age (n = 4), or they were classified as walkers based on the AIMS but could not be classified as novice or expert walkers due to missing parent questionnaire data on walking onset (n = 3).

Initial developmental level

Parents filled out the Ages and Stages Questionnaire (ASQ-2: Bricker & Squires, 1999) when their infants were 10 months old. The ASQ consists of five scales (Communication, Gross Motor, Fine Motor, Problem Solving, and Personal–Social), and each scale consists of 6 items. Because the ASQ is a developmental screener, scores tend to differentiate primarily at the lower end of the ability scale and may give a ceiling effect in a typically developing sample. The ASQ was included in the current study as a control measure of initial individual differences in development prior to walking onset. Therefore, to increase variability, we included all items from both the 10-month and 12-month versions, which showed partial overlap, resulting in 9 items per scale. For each item, parents indicated on a 3-point scale whether their children did a specific activity (no, sometimes, or yes). To create a general composite initial developmental measure that could be used as a control measure in the analyses, we computed the mean of the scales that were not focused on motor development: Communication, Problem Solving, and Personal–Social (inter-scale correlations ranged from .27 [$p < .05$] to .45 [$p < .001$], α = .75 across 27 items). Data were available for 72 of 77 infants (93.5%). The age at which the ASQ was filled out was on average 10.2 months (*SD* = 0.3, range = 9.6–10.9) and did not differ by group status, $F(2, 54) = 0.499$, $p = .610$. Note that 2 infants were reported to already show independent stepping at the age of parents' filling out the ASQ; both these infants were expert walkers at the 14-month lab visit.

Selective attention at 14 months

The selective attention task from Kaldy, Kraper, Carter, and Blaser (2011) was used. This is a visual search task that we administered on a Tobii T60 binocular eye tracker with a 17-inch LCD monitor (accuracy = 0.5°, sampling rate = 60 Hz). Children sat in a car seat that was strapped onto a desk chair in front of the eye tracker in a darkened room approximately 50 cm from the monitor. Parents sat or stood next to their children on one side, and an experimenter sat next to the children on the other side. The standard Tobii calibration procedure for infants with nine calibration points was used. In the task, which was completely nonverbal, infants were first shown the three test stimuli in two familiarization trials: a round red apple, a round gray apple, and a rectangular piece of a red apple. Subsequently, to highlight the special status of the red apple—the target—this stimulus was shown flying in from the corner of the screen to the fixation cross in the center while an attention-grabbing sound was played. Next, the first 2 test items were given. Both were feature trials that showed the red target apple among one type of distractor apples only. Thus, the target and distractors differed from each other by a clear feature (i.e., color or shape). After 4 s, the red apple started to rotate and a clapping sound was played. As such, infants learned to expect that the red apple would rotate and make a sound, providing an incentive for them to search for it. The remaining set of test items consisted of a mix of feature and

Table 2
Descriptives of success at finding the target for each item by group

			Proportion success at finding the target[a] [M (SD)]		
Trial	Type	Set size	Crawlers	Novice walkers	Expert walkers
1	Feature	5	0.93 (0.28)	1.00 (0.00)	0.93 (0.27)
2	Feature	5	0.79 (0.43)	1.00 (0.00)	0.88 (0.34)
3	Conjunction	9	0.64 (0.50)	0.56 (0.51)	0.87 (0.35)
4	Conjunction	5	0.82 (0.40)	1.00 (0.00)	0.93 (0.26)
5	Conjunction	9	0.31 (0.48)	0.60 (0.51)	0.63 (0.50)
6	Conjunction	5	0.73 (0.47)	0.80 (0.41)	0.88 (0.33)
7	Conjunction	13	0.50 (0.52)	0.47 (0.52)	0.50 (0.52)
8	Feature	9	0.93 (0.27)	0.93 (0.27)	0.88 (0.34)
9	Conjunction	9	0.75 (0.45)	0.54 (0.51)	0.87 (0.35)
10	Conjunction	5	0.67 (0.49)	0.62 (0.51)	0.73 (0.46)
11	Conjunction	5	0.20 (0.42)	0.67 (0.49)	0.81 (0.40)
12	Feature	9	0.67 (0.49)	0.75 (0.45)	0.73 (0.46)
13	Conjunction	9	0.54 (0.52)	0.70 (0.48)	0.71 (0.47)

Note. "Trial" represents the fixed order in which items were administered.

[a] Valid *n* cases on which proportion scores are based varies from 10 to 14 for crawlers, from 10 to 16 for novice walkers, and from 14 to 17 for expert walkers.

conjunction trials. Trial order was fixed, and no more than 2 trials of the same type and set size were presented after one another (see Table 2). In conjunction trials, the red target apple was shown among a mix of round gray and rectangular red distractor apples. As such, the target was unique by a combination of features (i.e., its shape and color). As with the first 2 feature trials, the procedure was as follows. Before each trial, the red apple flew in toward the center of the screen, and this movement was accompanied by a sound. Next, the red apple disappeared. Then, the red apple was shown together with the distractors in a static image for 4 s while a light ticking sound was played. After each test trial, the red apple started to turn and a clapping sound was played. The red target apple and gray distractor apples were about 4.1 * 4.1° visual angle, whereas the rectangular red distractor apples were about 7.8 * 1.5° visual angle. All stimuli were presented within a virtual circle around the fixation cross with a diameter of about 22.5° visual angle. Images of the stimuli are published in Kaldy et al. (2011).

To keep administration time short, infants were given a total of 4 feature trials (set sizes of 5 and 9) and 9 conjunction trials (set sizes of 5, 9, and 13). For each test trial, the target and distractors were defined separately as areas of interest (AOIs) with Tobii Studio (Version 3.2.1). AOIs were manually delineated, and each AOI was defined as the target or distractor shape, with no error margins around that shape. Target localization was coded as successful if infants had a fixation of at least 100 ms at the target AOI on that trial (i.e., a fixation of at least 100 ms at the static image of the red apple shown between the distractors within the 4 s before the red apple started to turn and the clapping sound was played). Fixations shorter than 100 ms are generally considered to be too short for information to be fully acquired at the fixated location (e.g., Pelz & Canosa, 2001). Success at finding the target within the given time limit on each trial was taken as the primary outcome measure reflecting effortful visual search, following Kaldy et al.'s (2011) and Rose, Wass, Jankowski, Feldman, and Djukic's (2019) work on the same task in toddlers.

Procedure

Shortly before infants reached 10 months of age, parents were sent the ASQ and a questionnaire in which they were asked to record the age of onset of gross motor milestones until the lab visit. When infants reached 14 months of age, parents and their infants were invited to the lab for a test session

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[1] For one of these infants, an expert walker, a research assistant report on whether the selective attention task was administered without problems was missing. This infant had only one valid test item and therefore was excluded from the analyses.

that included the selective attention task. Infants received a small gift after the lab session. This study received approval from the internal faculty board (Faculty's Advisory Committee under the Medical Research [Human Subjects] Act [WMO Advisory Committee]) at Utrecht University. Written parental consent was obtained before infants' assessment in the lab.

Analyses

Data screening and missing data. Responses to items in the selective attention task were included in the main analyses if the assessor reported that the task had been administered without problems and if infants fixated ($\geq$100 ms) at least once on either the target or one of the distractors (see also Kaldy et al., 2011). This criterion was met on at least 1 item for 14 of 23 crawlers (61%), 16 of 19 novice walkers (84%), and 17 of 22 expert walkers (77%), $\chi^2(2) = 3.159$, $p = .206$. The other children did not meet this criterion for various reasons such as crying or technical errors.[1] Thus, the sample size for analysis was 14, 16, and 17, respectively. Within the group of infants with test data, the mean number of valid items was 11.4 for crawlers (*SD* = 1.8, range = 8–13), 11.3 for novice walkers (*SD* = 2.2, range = 6–13), and 11.8 for expert walkers (*SD* = 2.4, range = 4–13), $F(2, 46) = 0.258$, $p = .774$, suggesting that the three groups responded to a similar number of items and were similarly engaged with the task.

A previous study using the same visual search task showed that children preferentially focused on the target (Kaldy et al., 2011). To study whether children in the current study also preferentially focused on the target, the mean fixation duration was computed for the targets and distractors separately across all valid items for each infant (following Kaldy et al., 2011). For this specific analysis, items were included only if infants focused on the target at least once for at least 100 ms. Across successful items, the mean fixation duration to targets was 0.43 s for crawlers (*SD* = 0.06), 0.41 s for novice walkers (*SD* = 0.11), and 0.49 s for expert walkers (*SD* = 0.12). Mean fixation duration to distractors was 0.33 s for crawlers (*SD* = 0.06), 0.32 s for novice walkers (*SD* = 0.09), and 0.35 s for expert walkers (*SD* = 0.08). Thus, infants in all three groups preferentially focused on the target as compared with distractors, with effect sizes being large for all groups (crawlers: $d = 1.59$; novice walkers: $d = 0.91$; expert walkers: $d = 1.31$).

In addition, given that we administered the visual search test to much younger children than in previous studies (see Kaldy et al., 2011; Rose et al., 2019), we explored whether infants' looking behavior was indicative of a pop-out effect on feature items and of effortful search on conjunction items across the sample, as would be predicted. To this end, we computed a "first look" variable, indicating whether infants looked at the target versus one of the distractors first. Raw data are shown in Table 3. For analytic purposes, we averaged the first look variable across feature trials with 5 versus 9 distractors and across conjunction trials with 5 versus 9 distractors. If feature items showed a pop-out effect, the proportion of infants looking at the target first would be much higher than chance; if conjunction items required effortful search, the proportion of infants looking at the target first should be lower than on the feature items but higher than chance. On all item types, the proportion of infants looking at the target first was higher than chance level (feature, 5 distractors: $M = .51$, $SD = .43$; feature, 9 distractors: $M = .32$, $SD = .37$; conjunction, 5 distractors: $M = .31$, $SD = .26$; conjunction, 9 distractors: $M = .26$, $SD = .29$; all *p*s < .012). However, note that the proportion of infants looking at the target first on the feature items with 9 distractors was only .32, indicating that there was not a strong pop-out effect. Next, we compared performance across item types. For items with 5 distractors, infants looked at the target first more often on feature trials than on conjunction trials, and the effect size was medium ($z = 2.981$, $p = .003$, $r = .44$). For items with 9 distractors, the effect was in the same direction but not statistically significant, and the effect size was small ($z = 0.767$, $p = .443$, $r = .12$). To summarize, the feature items were more easy than the conjunction items for the 14-month-old infants in our sample, but there was no evidence of a strong pop-out effect on the feature trials. This was particularly the case for the more difficult feature items (i.e., those with 9 distractors), which seemed to require at least some level of effortful search. Thus, these preliminary analyses show that the feature items in the visual search task that we used required at least some level of effort for the 14-month-old infants in our sample, and response patterns were not indicative of a strong pop-out effect on those trials.

Main analyses. To address our research question of how walking experience relates to selective attention test performance, we ran generalized linear mixed-effect regression analysis in the statistical pro-

Table 3
Descriptives of proportion of infants who focused on the target first for each item by group

				Proportion of infants that focused on the target first [*M* (*SD*)]		
Trial	Type	Set size	Chance level	Crawlers	Novice walkers	Expert walkers
1	Feature	5	.17	.93 (.27)	.73 (.46)	.64 (.50)
2	Feature	5	.17	.14 (.36)	.27 (.46)	.38 (.50)
3	Conjunction	9	.10	.18 (.40)	.25 (.45)	.20 (.41)
4	Conjunction	5	.17	.55 (.52)	.53 (.52)	.40 (.51)
5	Conjunction	9	.10	.23 (.44)	.20 (.41)	.19 (.40)
6	Conjunction	5	.17	.27 (.47)	.33 (.49)	.35 (.49)
7	Conjunction	13	.07	.17 (.39)	.13 (.35)	.06 (.25)
8	Feature	9	.10	.43 (.51)	.36 (.50)	.44 (.51)
9	Conjunction	9	.10	.25 (.45)	.15 (.38)	.40 (.51)
10	Conjunction	5	.17	.08 (.29)	.23 (.44)	.07 (.26)
11	Conjunction	5	.17	.10 (.32)	.50 (.52)	.31 (.48)
12	Feature	9	.10	.25 (.45)	.08 (.29)	.27 (.46)
13	Conjunction	9	.10	.23 (.44)	.30 (.48)	.43 (.51)

Note. 'Trial' represents the fixed order in which items were administered. [a]Valid *N* cases on which proportion scores are based varies from 10 to 14 for crawlers, 10 to 16 for novice walkers, and 14 to 17 for expert walkers.

gram R (R Development Core Team, 2015) using the *lme4* package (Bates, Mächler, Bolker, & Walker, 2015). The dependent variable in this analysis was infants' response on each item in the attention task (0 = target not found, 1= target found). Group (crawlers, novice walkers, or expert walkers), set size (5 or 9 distractors), and type (feature or conjunction) were included as fixed-effect factors, with an interaction between group and type. We included by-participant and by-item random intercepts to obtain the maximal random effect structure supported by the data. Because only 1 item had 13 distractors, creating a level for the variable set size with only 1 data point, this item was not included in the analysis. Orthogonal sum-to-zero contrast coding was applied to the categorical fixed-effect factors group, type, and set size (Schad, Vasishth, Hohenstein, & Kliegl, 2020). Specifically, contrasts were set such that crawlers were compared with novice and expert walkers (Contrast 1: crawlers −2/3, novice walkers +1/3, expert walkers +1/3) and novice walkers were compared with expert walkers (Contrast 2: novice walkers −1/2, expert walkers +1/2). In a second, exploratory analysis, the same model was run with two additional control variables: number of weeks since crawling onset at the time of the lab visit (henceforth "crawling experience") and initial developmental level prior to walking onset (mean ASQ score at 10 months of age). Because both variables were continuous, they were centered around zero in the analysis (Baguley, 2012). The *glmer* function provides a log odds estimate measure of effect size. However, because log odds values can be difficult to interpret, they were exponentiated to odds ratios for ease of interpretation. The data, scripts, and model output are available as supplementary material in the Open Science Framework (OSF) platform (https://osf.io/bae5m/?view_only=6c6157a4ffb241d59aa4c8eefb5efea0).

Results

Descriptive statistics

Mean proportion correct scores per item on the selective attention task are shown in Table 2. Crawling experience differed by group, *F*(2, 42) = 5.057, *p* = .011, and was larger for expert walkers (*M* = 27.2 weeks, *SD* = 6.5, range = 16.4–39.2) compared with crawlers (*M* = 19.6 weeks, *SD* = 8.3, range = 8.9–31.4). Effect size was large (*d* = 1.02, *p* = .008). There was no significant difference between novice walkers (*M* = 23.6 weeks, *SD* = 4.1, range = 17.4–29.6) and crawlers or between novice and expert walkers.

In addition, ASQ scores at 10 months of age were higher, but not significantly so, in expert walkers at 14 months (*M* = 1.23, *SD* = 0.29, range = 0.67–1.70) compared with novice walkers (*M* = 1.09, *SD* = 0.25, range = 0.67–1.59), which in turn were higher than in crawlers (*M* = 1.01, *SD* = 0.30, range = 0.70–1.85), *F*(2, 41) = 2.363, *p* = .107. The effect sizes for the group differences in ASQ scores ranged from small to moderate–large (crawlers vs. novice walkers: *d* = 0.30; crawlers vs. expert walkers: *d* = 0.75; novice vs. expert walkers: *d* = 0.52). Despite the lack of a statistically significant group difference in ASQ scores, we deemed these effect sizes large enough to include ASQ scores as a control variable in our analyses. The correlation between crawling experience and ASQ scores was *r*(43) = .27, *p* = .087.

Main analyses

A linear mixed-effect regression model on children's responses in the selective attention task with group, set size, and type as fixed effects showed a main effect of group for crawlers versus novice/expert walkers. Thus, crawling infants performed less well on the selective attention task than walking infants. There was no main effect of group for novice versus expert walkers. Furthermore, the model showed main effects of set size and item type, which indicated that children were more likely to find the target if there were 5 distractors rather than 9 distractors and if items involved feature search rather than conjunction search, respectively. Finally, the model showed a significant interaction between group and type, which signaled that the effect of item type (i.e., generally better performance on feature items than on conjunction items) was larger for novice walkers as compared with expert walkers (see Fig. 1). The interaction between the other group comparison (crawlers vs. novice/expert walkers) and item type was not significant. For an overview of the full model results, see Table 4.

Next, we explored whether the effects remained if the variables crawling experience and ASQ scores were entered as additional fixed-effect factors in the model. The results were largely similar to those in the previous model. Specifically, the effect of group remained significant, showing that both groups of walkers were more likely to find the targets than the crawlers irrespective of item type and set size. As in the previous model, moreover, there was a main effect of type, showing that children were more likely to find the targets for the feature items as opposed to the conjunction items. In addition, the interaction effect between group (novice vs. expert walkers) and type remained, showing that

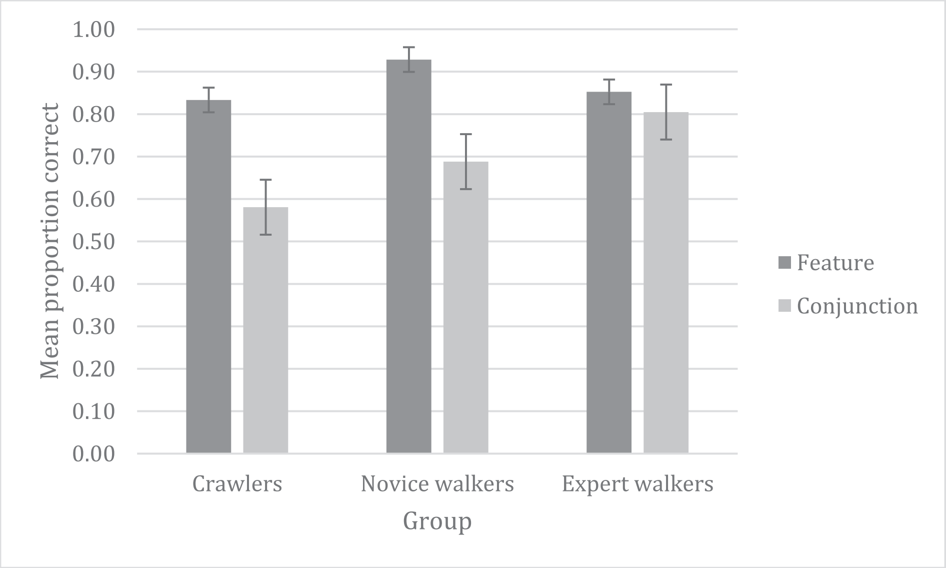

Fig. 1. Mean proportion success (±1 standard error) at finding the target by group for feature and conjunction trials.

Table 4
Results of a linear logistic mixed-effect model on infants' success on the items in the selective attention task with group, set size, and item type as fixed-effect factors (*n* = 14 crawlers, *n* = 16 novice walkers, *n* = 17 expert walkers)

	Unstandardized estimate (log odds)	*SE*	*z*	*p*	Odds ratio (95% CI)
Intercept	1.649	0.248	6.657	<.001	5.200 (3.200–8.449)
Group (crawlers vs. walkers)	0.799	0.389	2.053	.040	2.223 (1.037–4.766)
Group (novice vs. expert walkers)	−0.027	0.464	−0.059	.953	0.973 (0.392–2.414)
Item type	−1.281	0.417	−3.074	.002	0.278 (0.123–0.629)
Set size	−0.767	0.371	−2.065	.039	0.465 (0.224–0.962)
Group (crawlers vs. walkers) * item type	0.308	0.580	0.531	.595	1.360 (0.437–4.236)
Group (novice vs. expert walkers) * item type	1.599	0.726	2.203	.028	4.949 (1.193–20.524)

Table 5
Results of a linear logistic mixed-effect model on infants' success on the items in the selective attention task with group, set size, and item type as fixed-effect factors after controlling for crawling experience and development at 10 months of age (*n* = 13 crawlers, *n* = 16 novice walkers, *n* = 14 expert walkers)

	Unstandardized estimate (log odds)	*SE*	*z*	*p*	Odds ratio (95% CI)
Intercept	1.494	0.241	6.187	<.001	4.453 (2.774–7.148)
Group (walkers vs. crawlers)	0.968	0.419	2.307	.021	2.632 (1.157–5.988)
Group (novice vs. expert walkers)	−0.186	0.466	−0.399	.690	0.830 (0.333–2.071)
Item type	−1.231	0.418	−2.945	.003	0.292 (0.129–0.663)
Set size	−0.698	0.373	−1.872	.061	0.498 (0.240–1.033)
Crawling experience	−0.054	0.027	−2.021	.043	0.948 (0.900–0.998)
ASQ, 10 months	0.496	0.693	0.715	.474	1.642 (0.422–6.387)
Group (crawlers vs. walkers) * item type	0.380	0.589	0.644	.520	1.462 (0.460–4.640)
Group (novice vs. expert walkers) * item type	1.691	0.739	2.286	.022	5.422 (1.273–23.098)

Note. The sample size for the current model was *N* = 43 ,compared with *N* = 47 for the model in Table 4, due to 2 cases with missing data on the Ages and Stages Questionnaire (ASQ) 10-months variable: 1 case with missing data on the crawling experience variable and 1 case with missing data on both these variables. 95% CI, 95% confidence interval.

the effect of item type was stronger for novice walkers compared with expert walkers. Crawling experience also showed an effect, whereas ASQ scores did not. The remaining effects were not significant. For an overview of all model results, see Table 5.

Conclusion

Study 1 provides a first indication that walking experience may be related to selective attention at 14 months of age, and these results could not be accounted for by initial general developmental differences before walking onset or crawling experience. Actually, after controlling for individual differences in these two variables, crawling infants performed less well on the selective attention task compared with walking infants irrespective of item type (feature or conjunction). Specifically, crawling infants found fewer targets on the selective attention task in general. This was also evident in the percentage of infants who passed the criterion for including their data in the main analyses (i.e., if the assessor reported that the task had been administered without problems and if infants fixated [≥100 ms] at least once on either the target or one of the distractors), which was lower—although not significantly so—for crawlers (61%) compared with novice and expert walkers (84% and 77%, respectively). Crawling experience was included as a control variable to ensure that any effects of walking experience could not simply be explained by crawling experience. This variable was negatively related to task performance in the model; we stop short of interpreting this finding given that many—but not all—crawlers had learned to walk before they came to the lab.

Furthermore, walking status significantly interacted with item type, such that expert walkers showed less of a discrepancy in performance between feature and conjunction items compared with novice walkers. This result was obtained irrespective of whether differences in crawling experience and initial developmental differences at 10 months of age were included in the model. Thus, our hypothesis that walking experience relates positively to effortful visual search on a selective attention task was confirmed. Note, however, that a relatively large number of infants who were recruited to take part in the study were not included in the analyses for various reasons (e.g., lack of valid test items), and the sample size that remained was relatively small (47 of the 64 infants assigned to one of the locomotor groups, a 27% dropout rate). Thus, results of the study should be interpreted with caution and cannot be generalized until replication studies have confirmed the effects in larger samples.

Study 2

The results from Study 1 showed a positive association between infant walking experience and selective attention, but it is unclear whether this association remains when children grow older. Findings from previous studies on other cognitive domains are inconclusive in this regard; some have shown that the association between infant self-locomotion and language development attenuates after infancy (Oudgenoeg-Paz, Volman, & Leseman, 2016), whereas others have reported a significant positive association between age of walking onset and cognitive function during childhood (intelligence at 8 years of age) and adulthood (reading comprehension at 26 years of age; verbal fluency, but not reading, at 53 years of age) (Murray, Jones, Kuh, & Richards, 2007). However, in the latter study, associations with walking onset were no longer significant when the latest walking infants and individuals with low IQ (<70) were removed from the analyses. Furthermore, one study specifically investigated age of walking onset in relation to visual attention in early old age (mean age = 64 years) and found a significant positive association, although it was not investigated whether the association was primarily due to the latest walking infants (Clark-Poranen et al., 2015). To summarize, it is unclear whether the age of walking onset remains a predictor of visual selective attention beyond the infant years. Moreover, it is not clear whether long-term relations are only found due to the very late walkers. To address both these questions, we investigated the relationship between the age of walking onset and selective attention at toddler age using data from a large cohort study on early child development. To explore whether any effect of walking onset on selective attention could be attributed to the difference between late walkers and the rest of the group, both a continuous measure of walking onset and a dichotomous measure (early/average vs. latest 10% walkers) were used as predictors in separate analyses. In addition, we investigated whether the 10% latest walkers were also developmentally delayed in domains other than motor development, such that developmental delay would need to be included as a control variable in the analyses. To this end, we explored whether children in the late walkers group were delayed on another key aspect of child development during toddlerhood—language development.

Method

Sample

Data from the current study came from a large-scale longitudinal cohort study (Mulder, Hoofs, Verhagen, Van der Veen, & Leseman, 2014; Mulder, Verhagen, Van der Ven, Slot, & Leseman, 2017; Verhagen, Boom, Mulder, de Bree, & Leseman, 2019; Verhagen, de Bree, Mulder, & Leseman, 2017). Participating children were born between April and November 2008 and had been recruited from nurseries and playgroups and through directly approaching parents via a letter. Data reported on in the current study were collected during the first study wave when children were 2 years old. On the basis of a letter informing parents about the research project, parents signed for their children's

Table 6
Background characteristics and walking onset for toddlers with valid selective attention test data

	Full sample	Walking onset	90% early/average walkers	10% late walkers
	[*n*/total *N* (%)]	[*M* (*SD;* range)]	[*n*/total *N* (%)]	
Gender:				
Boys	453/922 (49%)	13.8 (2.4; 9–23)	400/453 (88%)	53/453 (12%)
Girls	469/922 (51%)	13.7 (2.3; 9–23)	427/469 (91%)	42/469 (9%)
Ethnicity:				
Dutch	705/915 (77%)	14.0 (2.3; 9–23)	623/705 (88%)	82/705 (12%)
Western non-Dutch	51/915 (6%)	12.7 (1.9; 9–17)	50/51 (98%)	1/51 (2%)
Non-Western non-Dutch	159/915 (17%)	12.8 (2.4; 9–21)	148/159 (93%)	11 (7%)
	[*M* (*SD;* range)]			
Parental education	3.3 (0.8; 1–4)		3.3 (0.8; 1–4)	3.4 (0.7; 1–4)
Age in months at test	27.5 (2.7; 24.0–35.8)		27.6 (2.7; 24.0–35.8)	27.3 (2.6; 24.1–34.8)

Note. Ethnicity was missing for 7 children and parental education was missing for 2 children.

participation (children tested at home) or declined through opting out (children tested at day-care centers).

For the current investigation, children were selected with parent questionnaire data about the age of walking onset. This information was available for 1466 children among the full sample of more than 3000 children. Within this sample, we excluded children with medical risks (preterm birth, birth weight < 2500 g, brain damage, hard of hearing or deaf, visually impaired or blind, physical disability, chronic disease, Down syndrome, autism, or medical risk status not reported or known by parents [e.g., due to adoption]). Furthermore, inclusion criteria were age at test $\geq$ 24 and $\leq$ 36 months in order to restrict the sample to 2-year-olds and age of walking attainment < 24 months. The latter criterion was applied to ensure that all children were able to walk independently at the age of the test (i.e., 2 years). After applying the exclusion and inclusion criteria, the sample included 1007 children.

Biographical information for children with valid test data (as further explained below) is shown in Table 6. Parental education and ethnicity were coded in the same way as in Study 1. Walking onset was related to child ethnicity, $F(2, 912) = 24.908$, $p < .001$, and parental education, Kendall's tau = .11, $p < .001$, such that children with Dutch ethnicity and higher parental education had later walking onset than children with Western non-Dutch or non-Western ethnicity and lower parental education. Walking onset was not related to gender, $F(1, 920) = 0.723$, $p = .395$, and age at test, Kendall's tau = $-.03$, $p = .233$. Approval for the study was obtained from both ethical advisory committees of the Faculty of Social and Behavioral Sciences of Utrecht University and the Department of Education of the University of Amsterdam.

Measures

Walking onset. Parents reported the age in months at which children learned to walk in a retrospective questionnaire. Specifically, parents were asked, "At which age did your child learn to walk independently?" This question was then followed by a definition of independent walking: "Your child walked through the room without support from you and without holding on to any furniture or a baby walker." Finally, parents were encouraged to look up the information if they did not recall the relevant age, using photos, videos, or the booklet from the well-baby clinic, following the approach in Bodnarchuk and Eaton (2004). Parents answered the question by ticking the age of their children in months. Answer options were given in monthly intervals from 10 to 17 months and were less precise at the extremes of the scale (the lowest answer option was "< 10 months" and the highest answer option was "after 22 but before 24 months"). Both the continuous measure of walking onset and a dichotomous variable representing the latest walkers (10th percentile) versus the rest of the sample (henceforth "early/average walkers") were used in the analyses. Although there is no "gold standard" cutoff point for identifying children at developmental risk, the 10th percentile cutoff point is commonly used in developmental work, for example in behavioral screening (Strengths and Difficulties

Questionnaire; Goodman, 2001) and developmental motor assessments (AIMS; Darrah, Piper, & Watt, 1998).

Selective attention. A computerized visual search task was used to assess selective attention at 2 years (Mulder, Hoofs, Verhagen, Van der Veen, & Leseman, 2014; Mulder, Verhagen, Van der Ven, Slot, & Leseman, 2017). In this task, children were encouraged to find targets as quickly as possible among a set of distractors and to point to these as soon as they had located them. The selective attention task was programmed in E-Prime 2.0 (Schneider, Eschman, & Zuccolotto, 2002). In a short practice phase, children were familiarized with three different stimuli (an image of a bear, a donkey, and an elephant that were similar in terms of size and color) and were taught that they should point only to the elephants. Before the start of each test item, children were given the instruction, "Now you must try to find all the elephants very quickly!" Subsequently, each item was shown for a total of 40 s. In each of the three items, children were shown a screen with 48 animals across eight columns of six animals each, including eight targets. Each column contained only one target. Children were not informed that this was the case. A number was shown above each column. When children pointed to an elephant in column number *x*, the assessor pressed the key with number *x* on the keyboard as quickly as possible and a blue line appeared through the target that children had found. As such, children did not need to remember which of the elephants they had already located. Children were encouraged to keep searching as fast as possible, and they were given feedback throughout each item to minimize memory demands of the task. The number of targets that children found per test item was used as a measure of accuracy (range = 0–8).

Productive vocabulary. Parents reported on their children's productive vocabulary by filling out the Dutch version of the MacArthur Bates Communicative Development Inventory (CDI) (i.e., N-CDI short form of Words and Sentences, Version B; Zink & Lejaegere, 2003). The CDI is a widely used parental checklist containing a list of words and phrases. Caregivers indicate for each word or phrase whether their children "understand" or "understand and say" the given word or phrase. In the current study, the productive part ("understand and say) of the short from of the Dutch CDI was used; it contains 112 words and phrases and has been validated for use with Dutch toddlers (Zink & Lejaegere, 2003). The total number of words that children produced was scored as an index of productive vocabulary. Norms for Dutch monolingual toddlers with 1-month age bands are available for the N-CDI for boys and girls separately for children aged 16 to 30 months. For the children in our sample within this age window (i.e., 24–30 months), the 10% latest talkers were identified based on the Dutch norm scores.

Analyses

Data screening and missing data. When children did not look at the screen at all for the full 40 s of an item on the selective attention task, as reported online by the RA, their data on that item were not used in the analyses. In addition, when children did not find any targets throughout the three test items, their item scores were not included in the analyses because in such cases we could not be certain that children understood the task (see also Mulder, Hoofs, Verhagen, Van der Veen, & Leseman, 2014; Mulder, Verhagen, Van der Ven, Slot, & Leseman, 2017). The vast majority of children (87%) had three valid test items (877 of 1007), whereas 3% had two valid test items (31 of 1007), 1% had only valid test item (14 of 1007), and 8% had no valid test items (85 of 1007). Both early/average walkers and late walkers had 2.7 valid test items on average (*SD* = 0.9, range = 0– 3 in both groups). The percentage of children with no valid test items was equally distributed between the early/average and late walkers groups (8.4% [76 of 903] and 8.6% [9 of 104], respectively).

Productive vocabulary scores were available for 50% of the total sample (498 of 1007) and 50% of the sample with valid test data (462 of 922) given that norm scores were available only for monolingual Dutch children aged 24 to 30 months. Within the subsample with valid test data, 6.7% (n = 31) were late talkers and 93.3% (n = 431) were early/average talkers. Table 7 shows the cross-tabulation of the walking (early/average vs. late) * talking (early/average vs. late) variables. There was no significant association between these two variables, $\chi^2(1) = 0.970$, $p = .363$. Thus, the 10% latest walkers in the sample were not significantly delayed in productive vocabulary development compared

Table 7
Cross-tabulation of early/average versus late walkers by early/average versus late talkers for monolingual Dutch children aged 24 to 30 months with valid selective attention test data

	Early/average talkers	Late talkers
Early/average walkers (*N* = 412)	93.7% (386/412)	6.3% (26/412)
Late walkers (*N* = 50)	90.0% (45/50)	10.0% (5/50)

with early/average walkers, and developmental delay in productive vocabulary was not included as a control variable in the main analyses.

Main analyses. To investigate how infant walking onset was related to selective attention performance at 2 years of age, a generalized linear mixed-effect regression analysis was performed similar to the analysis in Study 1 except that the number of correctly found targets per item on the selective attention task was used as the dependent variable rather than binary accuracy scores (target found vs. target not found per item). In this model, walking onset (in months) and age at testing (in months) were entered as fixed-effect factors, and an interaction between walking onset and age at testing was included to test whether the effect of walking onset might be relevant only for younger children (with lower overall walking experience). In addition, parental education and ethnicity were included as control variables because they were related to walking onset (see "Sample" section above). A by-participant random intercept was included, to obtain the maximal random-effect structure that was supported by the data. Orthogonal sum-to-zero contrast coding was applied to the categorical variable ethnicity (Contrast 1: Dutch ethnicity −2/3 vs. Western immigration background +1/3, non-Western immigration background +1/3; Contrast 2: Western immigration background −1/2 vs. non-Western immigration background +1/2). All continuous variables (i.e., walking onset, age at testing, and parental education) were centered around zero (Baguley, 2012).

In a second more exploratory analysis, we assessed whether the predicted association between walking onset and selective attention was driven by the late walkers. That is, we investigated whether the 10% latest walkers performed worse on the selective attention test compared with the rest of the sample. To this end, we dichotomized walking onset into a new variable labeled "walking group" containing two levels: "early/average walkers" versus "late walkers" (contrast: early/average −1/2 vs. late onset +1/2). We then tested for the effect of walking onset on selective attention performance, running the same model as above except that the variable "walking group" was entered instead of the continuous variable "walking onset." The data, scripts, and model output are available as supplementary material on the OSF platform (https://osf.io/bae5m/?view_only=6c6157a4ffb241d59aa4c8eefb5efea0).

Results

Descriptive statistics

Mean walking onset was 13.7 months (*SD* = 0.4, range = 9–23). Infants walking at 17 months or later comprised the 10% latest walking group (*n* = 104). Mean accuracy on the selective attention test was 3.4 for Item 1, 3.6 for Item 2, and 3.6 for Item 3 (*SD* = 1.7, 1.8, and 1.8, respectively, range = 0–8 on each item, *N* = 918, 902, and 887, respectively).

Main analyses

A linear mixed-effect model regression analysis with walking onset * age at testing as well as parental education and ethnicity as fixed effects showed an effect of walking onset, such that children who started walking earlier generally performed better on the selective attention task than children who started walking later. Moreover, the model showed a main effect of age at testing, which indicated that older children generally performed better than younger children. Furthermore, there were effects of parental education and ethnicity, such that children whose parents were more highly (vs. lowly) educated and children of Dutch ethnicity (vs. children with immigration backgrounds) gener-

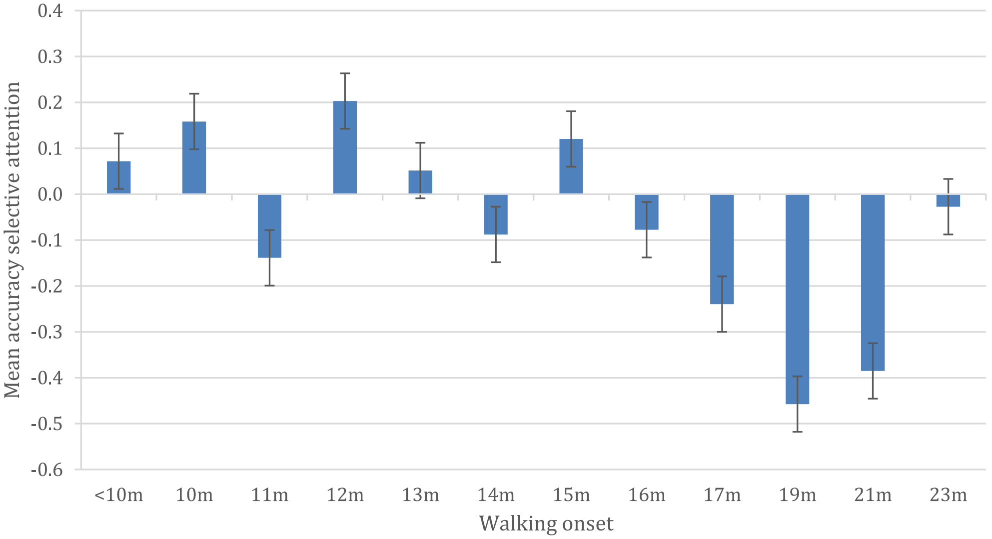

Fig. 2. Mean accuracy (±1 standard error) on the selective attention task by walking onset. Scores shown are residualized scores that are adjusted for testing age (m = months), ethnicity, and parental education.

Table 8
Results of a linear mixed-effects model on toddlers' performance on the selective attention task with age of walking onset and age at testing as fixed effects and parental education and ethnicity as fixed-effects control variables ($N = 913$)

	Unstandardized estimate	*SE*	*t*	*p*
Intercept	3.331	0.083	40.330	<.001
Age of walking onset in months	−0.052	0.021	−2.481	.013
Parental education	0.409	0.068	5.906	<.001
Ethnicity Dutch vs. immigration background	−0.334	0.135	−2.467	.014
Ethnicity Western vs. non-Western immigration background	−0.385	0.240	−1.600	.111
Age of testing in years	2.385	0.226	10.530	<.001
Walking onset * age of testing	−0.065	0.090	−0.724	.469

Table 9
Results of a linear mixed-effects model on toddlers' performance on the selective attention task with age of walking onset (dichotomous) and age at testing as fixed effects and parental education and ethnicity as fixed-effects control variables ($N = 913$)

	Unstandardized estimate	*SE*	*t*	*p*
Intercept	3.181	0.107	29.665	<.001
Age of walking onset (dichotomous)	−0.424	0.161	−2.628	.009
Parental education	0.399	0.069	5.800	<.001
Ethnicity Dutch vs. immigration background	−0.293	0.133	−2.205	.028
Ethnicity Western vs. non-Western immigration background	−0.377	0.241	−1.565	.118
Age of testing in years	2.297	0.373	6.160	<.001
Age of walking onset (dichotomous) * age of testing	−0.287	0.739	−0.388	.698

ally performed better on the task, respectively. The interaction between walking onset and age at testing was not significant. Fig. 2 shows the association between walking onset and selective attention test scores after controlling for test age, parental education, and ethnicity. For the full model results, see Table 8.

Our exploratory analysis in which we dichotomized walking onset to reflect the difference between the latest 10% walking children and the other 90% yielded results that are similar to those of the first model. Specifically, late walkers achieved lower scores on the selective attention task compared with early/average walkers. The results of this model are reported in Table 9.

Conclusion

In Study 2, walking onset was a significant predictor of selective attention test performance at 2 years of age when all children were already able to walk. Thus, we conclude that children with more walking experience were more proficient at effortful visual search at toddler age, similar to the results of Study 1. However, a follow-up analysis indicated that the association was primarily due to differences in selective attention test performance between late walkers and early/average walkers (see also Fig. 2).

General discussion

Given previous reports on the role of infant self-locomotion in the development of several cognitive domains, such as memory and language, the current study set out to investigate whether walking experience was related to selective attention task performance. Selective attention is a key factor underlying academic achievement in school-aged children (Stevens & Bavelier, 2012) and vocabulary acquisition in infants (Yu & Smith, 2011). Therefore, differences in selective attention related to walking experience may form a candidate mechanism through which walking experience affects cognitive domains. Previous work shows that attentional demands faced by walkers may be higher than those faced by crawlers (e.g., Oudgenoeg-Paz et al., 2015; Yamamoto et al., 2020). In addition, children with more walking experience have been reported to show more joint engagement with caregivers (Walle, 2016), and joint engagement with a caregiver increases duration of selective attention in infants (Yu & Smith, 2017). Therefore, we expected walking experience to be related to the development of selective attention. Results of Study 1 show that expert walkers at 14 months of age performed better than same-age novice walkers on conjunction trials in a visual search task. Conjunction trials require effortful search and serial scanning of the search array (Donnelly et al., 2007). Thus, the current study adds to existing literature by showing that infants with a significant amount of walking experience (i.e., having walked longer distances for > 4 weeks) are better at effortful search through a visual display than novice walkers of the same chronological age. Results of Study 2 show that the association between the age of walking onset and performance on another selective attention task that required effortful search still exists by toddlerhood, although this association appeared to be mainly due to the difference between late walkers (walking onset $\geq$ 17 months) compared with early/average walkers.

Although Study 1 confirmed the hypothesized difference in infant selective attention as a function of walking experience, further work is needed to investigate whether the proposed developmental mechanism, in which infant walking is *causally* related to selective attention development, is also supported. Note that the current study findings do point to a directional effect given that novice walkers struggled relatively more with the conjunction trials compared with the feature trials than expert walkers. Although there was no evidence of a clear pop-out effect for the targets in the feature trials in the young children in our study, the feature trials were less difficult than the conjunction trials and thus required less effort. If the direction of effects between walking experience and selective attention were the other way around—for example, because infants require a certain level of control over visual selective attention before they are able to maintain balance to be able to walk in the first place—we would expect novice and expert walkers to show the same level of performance on the selective attention task and on the conjunction trials in particular, whereas crawlers may perform worse. Instead, we found clear differences between novice and expert walkers, suggesting that walking experience is the important predictor. In addition, crawlers performed less well overall, irrespective of item type, and were also somewhat less likely to have valid test data in Study 1. Thus, it appears that crawling infants in Study 1 were less focused on and compliant with the demands of the task in general. To this end, our data are suggestive of the idea that a certain level of control over visual attention may be required for infants to learn to walk. Given that the current study was a cross-sectional investigation, we can only speculate about the direction of effects between infant walking experience and selective attention development based on the results. Future studies are clearly needed to rigorously test the direction of effects.

The differences in selective attention between groups at 14 months of age were not accounted for by individual differences in initial developmental level prior to walking onset at 10 months. Given that it is unclear from our data whether differences in selective attention at 14 months are accompanied by differences in other developmental domains at 14 months and beyond, much more work is needed to further establish whether the proposed mechanism from infant walking experience to cognitive advances through selective attention development is supported. First, a longitudinal investigation of the exact timing of walking onset in relation to changes in selective attention development is required, as are subsequent changes in, for example, memory and language. Second, to assess the amount of walking experience more accurately, a different assessment method is required rather than the very crude proxy measure of numbers of weeks of walking experience used in Study 1 or the walking onset variable used in Study 2. In particular, measures such as the number of steps infants have taken and distance they have traveled more truly reflect walking experience (Adolph et al., 2012). Third, the specific mechanism that we propose to underlie the relation between walking experience and selective attention requires further testing. Head-mounted eye-tracking studies may reveal the exact attentional demands faced by crawlers and walkers as they interact with objects and caregivers.

Study 2 showed that the age of walking onset remains a predictor of selective attention task performance during toddlerhood, yet the association appeared to be due to the difference between late and early/average walkers (see Fig. 2). Because infants with specific medical risk factors were excluded, parental education and ethnicity were controlled for in the analyses, and late walkers were not significantly more often developmentally delayed in other domains (i.e., productive vocabulary) than early/average walkers, it appears that biological and sociocultural factors are not likely to account for this finding—although unmeasured third variables may clearly still play a role.

The findings from Studies 1 and 2 are largely in line with findings for language development, where specific growth spurts have been identified following walking attainment during infancy (Oudgenoeg-Paz et al., 2012; Walle & Campos, 2014), whereas walking attainment no longer relates to language development during the preschool years (Oudgenoeg-Paz et al., 2016). We speculate that the timing of walking onset during infancy and its association with selective attention may potentially play a role in the lack of stability reported in other closely related domains of cognition during the second year of life such as executive functions (Miller & Marcovitch, 2015). Furthermore, Studies 1 and 2 show how development in one domain (i.e., motor skills) may relate to development in another domain (i.e., selective attention). Atypical selective attention in early life is a hallmark of disabilities such as autism spectrum disorder (ASD; Kaldy et al., 2011) and therefore may be a focal point of study for both clinicians and investigators working with young children at risk for ASD. Although it is clear that multiple roads might lead to the same developmental outcome in both typical and atypical development (see, e.g., the discussion by Oudgenoeg-Paz & Riviere, 2014), the current study shows that it is important to be aware of how different developmental domains may interact in early life. Such interactions may eventually lead, through a cascade of effects, to developmental outcomes seen in later life.

The findings are consistent with the ecological approach to development suggesting that the changes brought about by walking attainment are due to a change in children's affordances (Adolph, 2019; Gibson, 1988). Based on previous work showing that walking changes both perception and action because walking children are faced with more complex visual scenes (Kretch et al., 2014; Yamamoto et al., 2020) and are engaged in more complex actions where they combine the use of different affordances (Karasik et al., 2014; Oudgenoeg-Paz et al., 2015; Walle, 2016), we hypothesized that walking increases the attentional demands faced by infants and therefore will contribute to the development of selective attention. In terms of affordances, the affordance range available to infants grows as they learn to walk, and this growth probably forces them to actively select relevant affordances to focus on while ignoring others.

The current investigation included a carefully selected age-matched infant sample and an eye-tracking task to delineate attentional processes in Study 1 and data from a large cohort investigation in Study 2. Yet, several limitations need to be considered. First, the sample size for analysis in Study 1 was relatively small. Second, we were not able to explore effects of reaction time in Study 1 because infants were given a fixed amount of time to search on each trial and the task was relatively difficult for the age group we studied. As such, infants who did not find the target (which occurred frequently; see Table 2) did not have a valid reaction time. Given the relatively small number of items that we administered to keep test time short, a comparative analysis of reaction times on successful items across groups was not feasible. Therefore, we decided to use item success as the most appropriate outcome measure reflecting individual differences in effortful search, in line with previous studies using the same visual search task with young children (Kaldy et al., 2011; Rose, Wass, Jankowski, Feldman, & Djukic, 2019). Third, whereas in visual search studies on older children and adults participants are explicitly given a goal to search for, infants in Study 1 were nonverbally trained to search for the target. As such, we cannot be certain that all infants understood what was asked of them. However, infants in our study preferentially focused on the target compared with the distractors, and effect sizes were large in all groups (crawlers, novice walkers, and expert walkers), indicating that the training phase appeared to have been successful. Fourth, as previously mentioned, the current study does not provide evidence about the direction of the association between walking experience and selective attention development, and further work is needed in this regard. Fifth, although we aimed to investigate whether late walkers were delayed in other developmental domains as well in Study 2, this analysis was restricted to only about half the sample due to the lack of norms for the N-CDI for children aged over 30 months and children with a non-monolingual Dutch home language background.

To conclude, the current study has shown that walking experience relates to selective attention development close to the age of walking onset during infancy. At toddler age, walking onset is still related to selective attention task performance, but the association seems to be due to differences between late and early/average walkers. Our findings provide a first indication that walking experience relates to selective attention development, possibly due to the change in perception and action possibilities it brings about—a hypothesis that clearly requires further testing. In addition, future studies should investigate whether the observed association between walking experience and development in several cognitive domains, such as language, is mediated by changes in selective attention development.

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Appendix

Details on items used and reliability of AIMS assessment:

AIMS items

Two items from the Alberta Infant Motor Scale (AIMS) prone scale were scored separately for each child: "reciprocal creeping 1" and "reciprocal creeping 2." In the AIMS manual, these are described as follows. Reciprocal creeping 1: "This is an early creeping pattern characterized by the immature posture of the legs and lack of trunk rotation. The infant must move forward to pass this item" (Piper & Darrah, 1994, p. 84); reciprocal creeping 2: "This is a mature creeping pattern characterized by the mature posture of legs and trunk rotation. Lumbar lordosis is not present" (Piper & Darrah, 1994, p. 92). In addition, two items from the standing scale were scored for each infant: "early stepping" and "walks alone." In the AIMS manual, these are described as follows. Early stepping: "The infant must take five independent steps to pass this item. The position of the arms may vary from high guard to medium guard position. This item represents the infant's first attempts to walk independently; he or she may still fall often" (Piper & Darrah, 1994, p. 164); walks alone: "To pass this item, the infant uses walking as the main method of locomotion. The walking pattern may still be immature" (Piper & Darrah, 1994, p. 170).

Reliability of AIMS assessment

The vast majority of AIMS assessments were conducted by three different research assistants (RAs). A second coder rated the AIMS during at least a third of all sessions of each of these RAs (32%–40% double codes across 7–10 sessions). The percentage agreement with respect to the AIMS total score on the prone subscale was 100% for each RA. The percentage agreement between raters on the AIMS total score on the standing subscale ranged from 86% to 90%. In the few cases with disagreement, the difference between raters did not occur in the items relevant for the current study, that is, "early stepping" and "walks alone."

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