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ERP Dynamics of Learning Word-Object Associations

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Abstract

This dissertation investigated electrophysiological measures of individual differences in toddlers' ability to learn novel object labels and process familiar object words and their referents. The studies measured both visual and auditory event-related potentials (ERPs) in response to pictures of objects and words in a longitudinal sample of 20- to 24-month-olds, an age of dynamic vocabulary development. These ERP measures were related to the children's productive vocabulary size as well as behavioral measures of word comprehension and object recognition. *Study I* aimed to test children's ability to map familiar words to versions of their referents displaying reduced visual information (only overall shape or isolated parts), and if this ability correlated with vocabulary size. Children with larger vocabularies showed a stronger N400 incongruity effect in response to words paired with correct vs. incorrect shape referents specifically, and the N400 effect in the shape condition also correlated with the children's ability to overtly identify objects from their overall shape in a behavioral test. These results are discussed in relation to previous research demonstrating the emergence of a shape bias in children's word extension, as well as improvements in object shape recognition, during the second year of life. *Study II* investigated individual differences in novel word-object mapping and changes with age in this ability. The overall sample showed ERP evidence of novel word learning (an N400 semantic incongruity effect) after five consistent word-object pairings at 24 months but not at 20 months. Children with large vocabularies demonstrated the same linear attenuation of N400 amplitude during novel word repetition as is commonly seen in adults, while children with smaller vocabularies did not show such attenuation until the end of the learning phase. *Study III* focused on the 20 month data set and explored how visual ERPs were modulated as object-word pairs were presented repeatedly, and how these measures of visual object processing related to successful fast mapping of the novel words to the objects. A larger attenuation of the Nc component (associated with attention) predicted successful word learning, measured as a larger N400 incongruity effect to the novel words after training. Furthermore, better initial recognition of familiar objects correlated with a stronger N400 effect to the words for those objects. The results present novel evidence for a link between efficient visual processing of objects and word learning ability.

Taken together, this research demonstrates that the rapid vocabulary growth and striking individual differences in productive vocabulary development seen during children's second year are linked to the dynamics of specific brain mechanisms involved in semantic processing of words and their referents.

Key words: word learning, fast mapping, vocabulary development, children, ERP, N400, Nc

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List of Papers

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I. Borgström, K., Torkildsen, J. v. K., & Lindgren, M. (2015). Event-related potentials during word mapping to object shape predict toddlers' vocabulary size. *Frontiers in Psychology, 6*(143).

II. Borgström, K., Torkildsen, J. v. K., & Lindgren, M. (2015). Substantial gains in word learning ability between 20 and 24 months: A longitudinal ERP study. *Brain & Language, 149*, 33-45.

III. Borgström, K., Torkildsen, J. v. K., & Lindgren, M. (submitted). Individual differences in visual object processing predict rapid word learning ability in 20-month-olds.

Abstract

This dissertation investigated electrophysiological measures of individual differences in toddlers' ability to learn novel object labels and process familiar object words and their referents. The studies measured both visual and auditory event-related potentials (ERPs) in response to pictures of objects and words in a longitudinal sample of 20- to 24-month-olds, an age of dynamic vocabulary development. These ERP measures were related to the children's productive vocabulary size as well as behavioral measures of word comprehension and object recognition.

Study I aimed to test children's ability to map familiar words to versions of their referents displaying reduced visual information (only overall shape or isolated parts), and whether this ability correlated with vocabulary size. Children with larger vocabularies showed a stronger N400 incongruity effect in response to words paired with correct vs. incorrect shape referents specifically, and the N400 effect in the shape condition also correlated with the children's ability to overtly identify objects from their overall shape in a behavioral test. These results are discussed in relation to previous research demonstrating the emergence of a shape bias in children's word extension, as well as improvements in object shape recognition, during the second year of life.

Study II investigated individual differences in novel word-object mapping and changes with age in this ability. The overall sample showed ERP evidence of novel word learning (an N400 semantic incongruity effect) after five consistent word-object pairings at 24 months but not at 20 months. Children with large vocabularies demonstrated the same linear attenuation of N400 amplitude during novel word repetition as is commonly seen in adults, while children with smaller vocabularies did not show such attenuation until the end of the learning phase.

Study III focused on the 20 month data set and explored how visual ERPs were modulated as object-word pairs were presented repeatedly, and how these measures of visual object processing related to successful fast mapping of the novel words to the objects. A larger attenuation of the Nc component (associated with attention) predicted successful word learning, measured as a larger N400 incongruity effect to the novel words after training. Furthermore, better initial recognition of familiar objects correlated with a stronger N400 effect to the words for those objects. The

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Svensk sammanfattning

Barnets andra levnadsår präglas till stor del av en enorm utveckling av språkliga färdigheter. Omkring ettårsåldern börjar de flesta barn säga sina första ord. Det produktiva ordförrådet (de ord barnet kan säga) växer till en början ganska långsamt, men inlärningstakten ökar successivt. Mellan 1 ½ och 2 år genomgår många barn något som brukar kallas för ”ordförrådsspurt”, där inlärningen av nya ord tar ordentlig fart. Samtidigt börjar de ofta kunna kombinera ord till korta meningar. Lika slående som ordförrådens snabba utveckling i den här åldern, är de stora individuella skillnaderna i hur många ord olika barn kan säga. Medan ett barn vid 20 månader kan ha 250 ord i sitt produktiva ordförråd kanske ett annat barn bara kan säga 20 ord. Generellt ligger ordförståelsen långt före ordproduktionen, så barn förstår många fler ord än de säger. Ändå är förståelse och produktion av ord sammankopplade.

Den här avhandlingen tar sin utgångspunkt i ett intresse av att förstå vad som ligger bakom den snabba utvecklingen av ordförrådet samt de stora individuella skillnaderna i ordförrådets storlek bland barn i den här åldern. Specifikt undersöks hur barn med olika stora produktiva ordförråd skiljer sig åt vad gäller ordförståelse, det vill säga hur de faktiskt bearbetar ord som de hör och dessas referenter. För att kunna mäta dessa förståelseprocesser medan de pågår har en elektrofysiologisk utrustning (EEG) använts, som mäter hjärnans aktivitet kontinuerligt med en tidsupplösning på millisekundnivå. En stor grupp barn har fått titta på bilder av objekt som benämnts med ord. Detta har inkluderat både objekt som är välkända för små barn tillsammans med dess riktiga ord samt nya låtsasobjekt som benämnts med låtsasord för att simulera nyordsinlärning. Projektet är det första i sitt slag som bedrivits longitudinellt, det vill säga samma barn har fått utföra samma sorts uppgift vid 20 månaders ålder och sedan på nytt vid 24 månader. Analyserna fokuserade huvudsakligen på specifika händelserelaterade elektrofysiologiska signaler (s.k. event-related potentials: ERP) kopplade till bearbetningen av ett ords betydelse (N400) samt visuell uppmärksamhet av objekten (Nc). Även andra responser, t.ex. en respons kopplad till fonologisk bearbetning av själva ordet (ordets ljudform, som bearbetas före dess betydelse), analyserades. Dessa elektrofysiologiska mått relaterades sedan till mått på barnens språkförmåga och allmänna utveckling enligt föräldraskattningar samt ett explicit mått på ordförståelse och objektigenkänning i en separat uppgift, där barnen fick peka ut ords referenter bland bilder på flera olika objekt.

Tre olika studier utfördes som utforskade olika aspekter av det omfattande datamaterialet. *Studie I* undersökte barnens förmåga att koppla riktiga bekanta ord till sina objekt när bilderna på objekten endast visade övergripande form eller isolerade delar (t.ex. en ankas yttre siluett jämfört med ögonen, näbben och vingen av en anka). Tidigare forskning har visat att barn mellan 1½ och 2 år blir allt bättre på att uppmärksamma och identifiera objekt utifrån övergripande form, och att denna förmåga korrelerar med ordförråd. För att mäta hur effektivt barnen kopplade ett ord till det rätta objektet jämfördes deras respons till ordet när det presenterades med rätt objekt (bild av en anka följs av ordet ”anka”) med när ordet presenterades med fel objekt (bild av en hund följs av ordet ”anka”). Om bilden av objektet framkallat en förväntan hos barnet att höra ett visst ord, så bör man se en skillnad i ERP-respons när fel ord hörs jämfört med när det förväntade ordet hörs. Denna skillnad kallas för en N400 inkongruenseffekt och tolkas som att den semantiska bearbetningen av det rätta ordet (ordets betydelse) var mindre krävande tack vare den prediktion som bilden möjliggjorde. Resultaten visade att barnen överlag reagerade likadant på en inkongruens när orden föregåtts av vanliga bilder på hela objektet, oavsett deras produktiva ordförråd. Däremot fanns ett samband mellan barnens ordförråd och deras semantiska bearbetning av orden när de presenterades tillsammans med siluetter av objekten. Barn med större ordförråd visade en starkare N400 inkongruenseffekt i siluettbetingelsen än barn med mindre ordförråd. Detta indikerar att barn med större ordförråd hade lättare att känna igen objekten utifrån enbart form och således lättare aktiverade rätt ord. N400-effekten i siluettbetingelsen korrelerade även med vårt explicita mått på hur väl barnen kunde peka ut rätt objekt när de endast visades som siluetter.

Studie II undersökte hur barnens förmåga att snabbt koppla ett nytt ord till ett helt nytt objekt utvecklades från 20 till 24 månader, samt om det fanns relevanta individuella skillnader i hur barnen bearbetade de nya orden under pågående inlärning. Det visade sig att barnen vid 20 månader inte klarade av att helt koppla orden till objekten efter fem presentationer, men bara fyra månader senare klarade gruppen som helhet av samma uppgift. Detta visade sig som en signifikant N400-effekt till felaktiga ord-objekt-par jämfört med korrekta ord-objekt-par vid 24 månader, men ingen tendens till en sådan effekt fanns vid 20 månader. Vid båda testtillfällena påvisades ett samband mellan storleken på barnens ordförråd och hur deras semantiska bearbetning av orden förändrades under inlärningsfasen, som omfattade fem presentationer av varje nytt ord-objekt-par. Barn med större ordförråd visade en linjär minskning av N400-responsen för varje presentation, vilket indikerar att de för varje ytterligare presentation bearbetade kopplingen mellan ordet och objektet lite lättare. En sådan minskning av N400-responsen vid upprepning är karaktäristisk hos vuxna. Barn med mindre ordförråd däremot uppvisade en sådan minskning av N400 först mot slutet av inlärningsfasen. Detta indikerar att barn med mindre ordförråd behövde fler presentationer innan de började koppla ihop ordet

med objektet. Måttet på den fonologiska bearbetningen av orden förändrades däremot enligt samma mönster oavsett språkkompetens. Skillnaden som var relevant för ordförrådet låg således specifikt i bearbetningen av ordens betydelse, inte ordens ljudform i sig.

Slutligen fokuserade *Studie III* på datamaterialet från 20 månader, då gruppen som helhet inte klarade av att lära sig de nya ord-objekt-associationerna under experimentet. Vi undersökte om det fanns en mindre grupp barn som klarade detta bättre, och i så fall vad de hade gemensamt. Vi intresserade oss för hur barnen bearbetade de nya objekten under inlärningen, då de successivt blev mer bekanta. Därför analyserades visuella ERP-responser (hjärnans reaktion på endast bildvisningen innan ordet presenterades) och hur dessa förändrades under inlärningsfasen. Vi fann att en respons som relateras till uppmärksamhet och intresse (Nc) minskade linjärt för varje ytterligare gång ett objekt visades. Detta tyder på att barnens uppmärksamhet och intresse minskade något allteftersom objekten blev mer bekanta. Det visade sig att styrkan på den här upprepningseffekten predicerade N400-effekten till orden, så att barn vars uppmärksamhet minskade snabbare i större utsträckning reagerade på felaktiga parningar av orden och objekten i testfasen. Den grupp av barn som hade starkast repetitionseffekt på Nc-responsen visade också en statistiskt signifikant N400 inkongruenseffekt till de nyinlärda orden. Detta kan tyda på att de barn som snabbare lyckades skapa en representation av de nya objekten, och således ”tröttnade” lite fortare när de upprepades, hade bättre förmåga att lära sig vad objekten kallades. Det tyder i sin tur på att det inte bara är ordbearbetning som är relevant för förmågan att lära sig nya ord, utan även förmågan att snabbt känna igen och skapa representationer av objekt.

Sammantaget visar resultaten från den här forskningen att skillnader i barns produktiva vokabulär (hur många ord de kan säga) i åldern 20-24 månader kan kopplas till specifika och snabba processer i hjärnan involverade i att bearbeta och förstå ord och objekt samt deras inbördes relation. Överlag sker på enbart fyra månader en stor förbättring av barns förmåga att snabbt förstå kopplingen mellan nya ord och objekt, samtidigt som det produktiva ordförrådet i genomsnitt tredubblas under samma period. Barn med stora ordförråd visar tecken på att snabbare uppfatta ett nytt ords betydelse än barn med små ordförråd, trots att uppgiften endast kräver passiv bearbetning av stimuli och inte att orden ska uttalas. Dessutom verkar även visuell bearbetning av objekt spela en roll i utvecklingen av ordförrådet, då barn som mer effektivt bearbetade nya objekt hade större chans att lära sig vad objekten hette. Vi fann också stöd för teorin att tillväxten av det produktiva ordförrådet i den här åldern är kopplad till en ökad förmåga att känna igen den övergripande formen hos objekt. Detta kan höra ihop med att objekt ofta är kategoriserade utifrån likheter i form och att ökad erfarenhet av benämning ökar uppmärksamheten för de visuella egenskaper som objekt har gemensamt.

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Introduction

One of the greatest challenges children face during their second year of life is acquiring language. Most children go from producing only a few words at 12 months to combining several words flexibly and boasting a productive vocabulary of over 250 words one year later (Fenson et al., 1994). As will be described in the sections that follow, there is enormous variability between children as to how fast their vocabularies grow during this early phase of language acquisition. While one 18-month-old might be already producing sentences, another may not have started talking at all. At the heart of this dissertation lies an interest in the brain processes that underlie these individual differences. The studies reported measured online electrophysiological processes of novel word learning as well as the semantic processing of already familiar words and their referents, in a longitudinal sample of toddlers. We explored the relation between these online measures of brain processes and children's actual vocabulary size (as reported by their parents), and the relation between aspects of visual object processing and semantic word processing. This research is relevant not only to the area of language acquisition, but to the area of memory development and learning in infancy and early childhood in general. Therefore, the background section will cover research on vocabulary development as well as memory development and learning, and how the brain is involved in these processes.

Early Vocabulary Development

A person's vocabulary is the collection of words that the person knows, and the knowledge of words can be represented at different levels. For adults, most words that we understand we are also able to produce, although it usually takes a higher level of confidence in order to spontaneously use a word than it takes to be able to comprehend it in a context. When we talk about young children's vocabularies, the distinction between these two levels of vocabulary is even more important. The receptive, or passive, vocabulary comprises the words that a child understands, whereas the productive vocabulary includes only the words that the child actually says and uses. In the sections that follow, I will describe how these two aspects of vocabulary generally develop during the first years of life, and what we know about individual differences in this domain.

General patterns

The process of word learning starts very early, as the newborn infant tunes into his or her new environment and pays extra attention to social and linguistic input. Newborns prefer human speech to other auditory stimuli, and prefer human faces to non-facelike patterns (Johnson, Dziurawiec, Ellis, & Morton, 1991; Valenza, Simion, Cassia, & Umiltà, 1996; Vouloumanos & Werker, 2007), suggesting that they are prepared to attend to stimuli that are relevant for communication. In fact, it seems a foundation for language learning is laid already in the womb, as recent evidence has shown that even prenatal experiences influence infants' auditory discrimination abilities (Partanen et al., 2013). Over the course of their first few months, infants lay the foundation for building a vocabulary, by learning to identify the segments of speech that carry meaning. Already from birth, infants are able to discriminate nearly all phonetic contrasts in their own language as well as others (e.g. Streeter, 1976). But they have to learn which parts of a stream of speech constitute words. In order to do this they rely on statistical regularities about which phonemes tend to co-occur. By 8 months they are quite proficient at this task, and are able to identify novel words from only statistical information in 2 minutes (Saffran, Aslin, & Newport, 1996). Infants were long thought not to start learning the meanings of words until after 9 months, closer to their first birthday, because of younger infants' apparent difficulty understanding other's communicative intentions and the referential nature of words (e.g. Tomasello, 2001). Recent experiments, however, have shown that already 6- to 9-month-old infants know the meanings of common object words, beyond the words "mommy" and "daddy" (Bergelson & Swingley, 2012, 2014; Tincoff & Jusczyk, 1999). Infants' knowledge of word meanings was tested using looking time to videos/pictures of the correct referent compared to a distractor. These results are confirmed by event-related potential measures that have shown evidence of word comprehension in 9-month-olds, and at least some sensitivity to word meaning in 6-month-olds (Friedrich & Friederici, 2011; Junge, Cutler, & Hagoort, 2012; Parise & Csibra, 2012).

Thus, there is reason to believe that infants' receptive vocabularies start emerging at around 6 months of age. But it will take another half year for most infants before they start to produce words. This head-start for the receptive vocabulary over the productive one persists for the next few years. According to parent ratings, 50 % of Swedish 8-month-olds understand approximately 5 words at 8 months, and 45 words at 12 months. Even infants in the 10th percentile are reported to understand 5 words by 10 months. Moreover, there seems to be a tendency for parents to underestimate their children's receptive vocabulary (Houston-Price, Mather, & Sakkalou, 2007). Although it is not uncommon for infants to reportedly produce a handful words between 10 and 12 months, most children say their first words around their first

birthday. At this time, 50 % of Swedish children produce 4 words, and although there are individual differences, even those in the 90th percentile produce only around 10 words. Figures 1 and 2 show percentile curves of receptive and productive vocabularies as measured by the Swedish Early Communicative Development Inventories (SECDI) (Eriksson & Berglund, 2002). These patterns resemble those reported by the American version of the same instrument, the MacArthur-Bates Communicative Development Inventories, although Swedish infants seem to have slightly smaller productive vocabularies overall than American infants (Dale & Fenson, 1996).

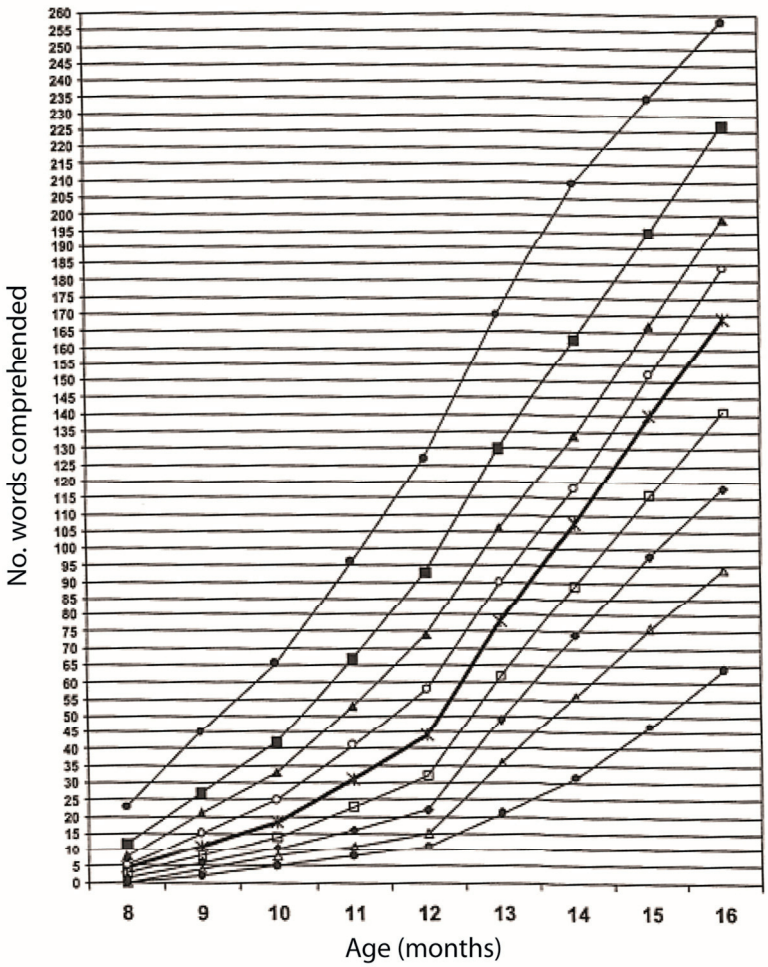

Figure 1. Comprehension vocabulary norms as measured by the SECDI, Words and Gestures (reproduced from Eriksson & Berglund, 2002, with permission from the authors).

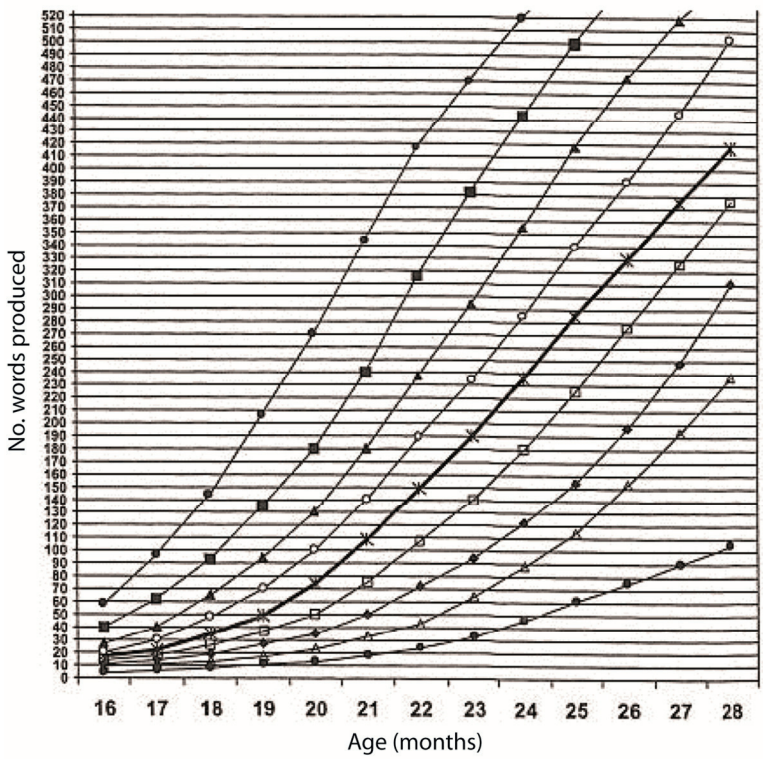

Figure 2. Productive vocabulary norms as measured by the SECDI: Words and Sentences (reproduced from Eriksson & Berglund, 2002, with permission from the authors).

The vocabulary spurt

The growth of the productive vocabulary in infants is typically described as starting out slow, with the 1-year-old learning only a few new words each month, and then suddenly speeding up, so that the same child learns 100 new words between 20 and 24 months of age. This increase in the rate of learning is referred to as the *vocabulary spurt* or *naming explosion,* and is said to take place after a child acquires a productive vocabulary of around 50-100 words (Ganger & Brent, 2004; Goldfield & Reznick, 1990). The 50-word threshold has therefore commonly been seen as a developmental milestone, indicating a change in a child's word learning ability. Many theories have been offered as to why the vocabulary spurt takes place. According to one suggestion, it is the result of a *naming insight*, the realization that all things can be categorized and have names (e.g. Kamhi, 1986). This insight is said to change the significance of words for the child, giving words a true referential value. Another theory argues that the spurt is due to the emergence of linguistic constraints, such as assumptions that words refer to whole objects, generalize to other things that are similar in kind, and that each thing only has one label (the mutual exclusivity assumption) (Markman,

1990). Other ideas are that an improved ability to categorize objects (Gopnik & Meltzoff, 1987) or an improved word segmentation ability (Plunkett, 1993) leads to an acceleration in vocabulary growth. A more recent theory is that the productive vocabulary spurt comes from improvements in word retrieval ability (Dapretto & Bjork, 2000). This theory emphasizes the different demands on being able to understand a word and actually producing it. In order to understand a word one has to recognize the lexical item and retrieve a semantic representation associated with it, while word production requires retrieving a phonological representation associated with an object. Since infants are able to mentally represent objects and events well before they can speak, and objects and events are meaningful in themselves while words are simply sounds that are assigned meaning from without, word retrieval should be more difficult than the retrieval of a representation of an object or event. This theory explains the discrepancy between receptive and productive vocabulary in a way that other theories of the vocabulary spurt fail to do. Other theories predict improvements in word comprehension abilities as well as production when in fact a spurt in receptive vocabulary takes place several months before the productive vocabulary spurt (Dale & Fenson, 1996).

In addition to the many theories about why a productive vocabulary spurt should take place, there is a debate as to whether it really does take place. Ganger and Brent (2004) discuss the fact that a spurt has long been assumed, but when individual rates of vocabulary growth are examined there is often no evidence of a sudden increase. Instead, vocabulary acquisition often shows a steady rate of increase. According to certain calculations approximately 13-18 % of children showed evidence of a real vocabulary spurt (Ganger & Brent, 2004), when defined as a clear change in growth rate. Still, even if there may be no distinct spurt, it is a fact that the rate of vocabulary learning increases substantially during the second year. It is likely that this increase in learning rate is due to improvements in several cognitive abilities that are relevant for word learning, and it is clear that there is still much to be learned about specific contributions.

Individual differences

When examining figures 1 and 2 with data from the SECDI, the large variability in vocabulary size at any given age is striking. One two-year-old may have a productive vocabulary of 460 words (80th percentile) while another uses only 80 words (20th percentile), although they are both perfectly normally developing children. What causes these differences? And do the differences matter? That is, does this difference at 24 months predict differences in language skills or other cognitive skills at a later age? These are interesting but difficult questions which I will try to address in the following sections.

Causes of individual differences in vocabulary size

As with the development of other cognitive abilities, there are of course many factors that contribute to a child's ability to build a vocabulary. In general, we can differentiate between *external/environmental* and *internal/individual* factors. External factors are those that influence a child's environment and thereby create different opportunities for a child to acquire a vocabulary. One external factor that has been systematically related to differences in language skills is socio-economic status (SES). A recent longitudinal study found that, in a sample of American children, SES was significantly related to vocabulary size (as measured by the CDI) as well as measures of online language processing efficiency (accuracy and speed of looking to a target referent named in continuous speech) already at 18 months (Fernald, Marchman, & Weisleder, 2013). Children from lower-SES families had smaller vocabularies and were also less efficient at real-time processing. At 24 months there was in fact a 6-month gap between children from high vs. low SES families. These results extend previous findings of positive correlations between SES and vocabulary skills (e.g. Arriaga, Fenson, Cronan, & Pethick, 1998; Hart & Risley, 1995) by showing that this difference is related to actual language processing efficiency and cannot be explained by for instance underreporting by parents with a lower level of education. The relation between SES and language skills is not surprising considering the large body of research documenting SES effects on cognitive development in general (for a review, see Bradley & Corwyn, 2002). However, it is worth noting that the effect of SES on language skills depends on how large the differences in level of SES are in a given community. A study examining Swedish 18-month-olds found no effect of SES on language skills measured with the SECDI, which is probably due to relatively small differences in SES compared to those found in US communities (Berglund, Eriksson, & Westerlund, 2005).

Attendance in childcare, both at the preschool level and early day-care, has generally been found to be positively associated with vocabulary, what might be explained by a counterbalancing of the effect of less advantageous family situations, as well as the general positive impact of a stimulating environment (Berglund et al., 2005; Burchinal, Lee, & Ramey, 1989; Burchinal & Roberts, 2000). An effect of gender and birth-order is also generally found, with girls and first-born children having an advantage (Berglund et al., 2005; Hoff-Ginsberg, 1998; Pine, 1995). These effects are considered small however, and the effect of birth-order is seen primarily on the earliest vocabulary, up to 50 words, but not on further vocabulary growth.

The factors described so far have something in common. Their influence on vocabulary growth is likely to be, at least in part, mediated by one common factor, namely language input. A larger amount of speech directed at a child is associated with a larger productive vocabulary, already during the second year (Huttenlocher, Haight, Bryk, Seltzer, & Lyons, 1991). The amount of child-directed speech, in turn,

is associated with SES, such that parents with higher SES tend to talk more to their children (Hoff-Ginsberg, 1991; Rowe, 2008). Similarly, it has been shown that parents tend to talk more directly to first-born children, and mothers talk more to their young daughters than to their sons (Johnson, Caskey, Rand, Tucker, & Vohr, 2014; Jones & Adamson, 1987; Wellen, 1985). The effect of speech input on productive vocabulary has, in turn, been shown to be mediated by the child's language processing efficiency (Weisleder & Fernald, 2013). It is not only the quantity of speech input that is significant for language development, but also the quality of the input. Specifically, input that is lexically diverse and syntactically complex is associated with larger vocabularies and better language development in children (Hoff & Naigles, 2002; Pan, Rowe, Singer, & Snow, 2005; Weizman & Snow, 2001).

Moreover, it is not only the verbal language input that influences children's language development, but also non-verbal communicative actions. For instance, maternal responsiveness, i.e. the extent to which mothers respond promptly, contingently and appropriately to their children's activities, is related to the timing of several milestones in expressive language (Tamis-LeMonda, Bornstein, & Baumwell, 2001). Related to this is the concept of joint attention, which can be defined as "parents' and children's coordinated attention to each other and to a third object or event" (Akhtar & Gernsbacher, 2007, p. 195). The number of joint attention episodes that take place between parents and children is positively correlated with children's vocabulary size (Smith, Adamson, & Bakeman, 1988; Tomasello & Farrar, 1986). According to some theorists, joint attention is a critical element in language acquisition, and the ability to engage in joint attention is the very reason that young children are able to learn the meanings of words (e.g. Tomasello, 2008). Tomasello argues that in order to learn what words mean we must be able to infer the speaker's intentions, and joint attention provides the foundation for attaining shared intentionality. A series of electrophysiological studies have demonstrated that eye contact from an adult enhances infants' attention when viewing novel objects, and improves their word learning (Hirotani, Stets, Striano, & Friederici, 2009; Striano, Reid, & Hoehl, 2006). Although there is empirical evidence for an association between joint attention activities and vocabulary development, the idea that joint attention is necessary or critical for language acquisition has been questioned. It is entirely possible to achieve word learning even without the ability to engage in joint attention, which is exemplified by word learning in children with autism or William's syndrome (Akhtar & Gernsbacher, 2007).

The case of joint attention brings us to the second class of factors influencing vocabulary development, namely *individual* factors. Joint attention can be considered an external factor, in the sense that parents offer a certain amount of interaction enabling joint attention. But we can also recognize that children, at any given age, differ in their ability to engage in joint attention. Regardless of the cause of such

differing abilities, this may be considered as an individual cognitive factor that could influence vocabulary development. In fact, the ability to engage in joint attention (e.g. the following of gaze towards an object combined with eye contact, or the pointing to an object combined with eye contact) at 12 and 18 months of age has been found to predict vocabulary size at 24 months, after controlling for general aspects of cognitive development (Mundy et al., 2007). Even a very early precursor of joint attention, the ability to follow the mother's gaze at 3 and 6 months, has been shown to predict word comprehension at 12 months (Silvén, 2001).

Other cognitive factors even more closely tied to language processing, such as speech perception skills, also influence word learning. For instance, phonetic discrimination skills in infants are associated with later vocabulary development. At birth, infants are able to discriminate between all phonemes, across languages, but at around 6 months they start a transition towards being better at discriminating phonemes in their native language than in other languages. Infants who reach this point of transition later are likely to have smaller productive vocabularies and produce less complex sentences than their peers at 24 months (Kuhl, Conboy, Coffey-Corina, Padden, & Nelson, 2008; Kuhl, Conboy, Padden, Nelson, & Pruitt, 2005). Similarly, the ability to segment words in continuous speech at 7 months is also positively associated with vocabulary size at 2 and 3 years (Kooijman, Junge, Johnson, Hagoort, & Cutler, 2013; Singh, Reznick, & Xuehua, 2012). At a higher level of processing, efficiency of word recognition at 18 months predicts faster vocabulary growth between 18 and 30 months (Fernald & Marchman, 2012). In this case, word recognition was measured by the speed and accuracy of looking to a target object when it was labelled in continuous speech. Thus, efficiency of receptive word comprehension in continuous speech is correlated with subsequent productive vocabulary growth. This has been demonstrated using other paradigms as well, for example event-related potential measures (Junge, Kooijman, Hagoort, & Cutler, 2012).

A recent review of speech perception measures as predictors for language development concluded that although there are several such linguistic measures that significantly predict subsequent language skills, the correlations for these measures are not stronger than other non-linguistic predictors of language development (Cristia, Seidl, Junge, Soderstrom, & Hagoort, 2013). Such non-linguistic predictors include basic auditory processing of nonlinguistic stimuli, and visual habituation and dishabituation measures. The ability to categorize brief, rapidly changing basic sounds in early infancy has been shown to be a significant predictor of later language outcomes and specific language impairment (Benasich, Thomas, Choudhury, & Leppänen, 2002). Habituation to repeatedly presented visual stimuli, measured as a decrease in look duration, as well as dishabituation which is an increase in look duration to subsequent novel stimuli, have been associated with language measures such as vocabulary size in many studies (e.g. Colombo, Shaddy, Richman, Maikranz, & Blaga, 2004; Tamis-LeMonda & Bornstein, 1989). While basic auditory processing skills can be thought

of as a foundation for speech processing, the measures of visual habituation and dishabituation are considered indicators of general information processing and memory skills, and have been used as predictors for later intelligence (e.g. Fagan & McGrath, 1981). Thus, individual differences in vocabulary size in toddlers are in part associated with differences in general cognitive skills.

Stability of individual differences in vocabulary size

When discussing individual differences in early vocabulary size, a natural question that arises is whether these differences in children as young as 1 or 2 years old actually tell us anything about what language skills these children will have at age 3, 5 or 10. What do we know about the stability of individual differences in vocabulary size specifically, and what is the predictive value of early vocabulary for language or other cognitive skills later on?

Through the infant-toddler years, the CDI measures show substantial correlations between productive vocabulary at different ages, where approximately 50 % of the variance in vocabulary at 20 and 27 months can be explained by vocabulary 6 months earlier (L. Fenson et al., 1994). This predictive validity over the toddler years has been confirmed by a study on a New Zealand population showing good predictive validity (correlations between r = .43 and .50) for productive vocabulary measures between 1 ½ and 3 years (Reese & Read, 2000). However, some larger-scale studies have reported lower, yet significant, correlations between expressive vocabulary at 18-24 months and language measures at 30-36 month, ranging from r = .32 to .34 (Feldman et al., 2005; Henrichs et al., 2011).

A large vocabulary around 2 years is also associated with better development in other language domains, such as syntax (McGregor, Sheng, & Smith, 2005; Moyle, Weismer, Evans, & Lindstrom, 2007). In fact, vocabulary size at age 2 has been found to significantly predict language and literacy skills up to at least age 11 (Lee, 2011). Interestingly, a recent longitudinal study found that the pace of vocabulary growth specifically, at 30 months, predicted vocabulary skills at 4 ½ years (Rowe, Raudenbush, & Goldin-Meadow, 2012).

Although measures of early vocabulary clearly have a significant predictive value of future language skills, the correlations are far from perfect. For an individual child it is still the case that a 2-year-old with very limited vocabulary often turns out to have excellent language and literacy skills in school. In fact, the value of parent-rated vocabulary measures in the toddler years for predicting a diagnosis of language delay a couple of years later is considered fairly low (Feldman et al., 2005; Henrichs et al., 2011; Westerlund, Berglund, & Eriksson, 2006). A recent doctoral dissertation explored the relation between vocabulary at 18 and at 24 months in a Swedish population, measured with the SECDI. The most striking observation was that there was much greater stability among the group in the highest quartile, with nearly 99 %

of children falling in the highest quartile at 18 months retaining their position at 24 months. However, children scoring in the lowest quartile at 18 months were almost evenly distributed among the four quartiles at 24 months (Eriksson, 2014). In other words, the children with the largest vocabularies are likely to remain precocious, while it is much more difficult to predict the development of children who lag behind at an early age. There are a variety of reasons why children in the lowest quartile produce relatively few words, and only some of them will actually have difficulties with language development. The data in this particular dissertation covered a very short period of development, only 6 months, but the general pattern of lower stability among the children with poorest vocabulary skills has been observed previously (Fernald & Marchman, 2012).

Word Learning and the Brain

Word learning and memory processes

Words and what they refer to is only one of many things that infants need to learn about the world. They have to learn to recognize faces in order to recognize their parents, they learn to recognize and categorize objects, and after gaining reasonable control over bodily movements they learn that fun things happen when they press a particular button on their favorite toy. In short, they learn associations between many different stimuli: objects and events, actions and events, people and objects, and associations between any of these stimuli and the sounds that make up a spoken word. So how does the process of learning the meaning of words relate to the process of learning other things about the world? In the following sections, I will first briefly review common models of different memory systems, and more thoroughly describe what we know about the forming and retrieval of word meaning representations in the adult brain. Then the story will be complicated by the fact that young children's brains differ from those of adults. Therefore, I will outline what research has shown concerning memory development in infancy, and how the memory processes that are functional early in development underlie children's ability to learn words and start building a vocabulary.

Models of declarative memory

An important distinction in the area of human long-term memory is that between declarative and non-declarative memory, where declarative memory is knowledge that we have conscious access to, while non-declarative memory is knowledge that has been implicitly acquired and is used without conscious awareness (Squire, 2004; Squire & Zola-Morgan, 1988). Declarative memory in turn is commonly divided into episodic memory for specific events and experiences, and semantic memory which is generalized knowledge about things in the world, abstracted from the specific learning experience. Tulving (1993) emphasized the role of autonoetic awareness in episodic memory, which he described as the ability of mental time-travel, where one is consciously aware of the time in which an event took place. Semantic memory on the other hand does not involve the re-experience of a learning event, instead the process of knowing something about the world is described as a noetic awareness. While episodic memories are *remembered,* semantic memories are simply *known.* Words and their meanings are represented in this general semantic memory system, in what can be described as a *mental lexicon*.

Memory processes can also be defined in terms of how information is accessed. An item can be retrieved through direct and active recollection of an item (recall), or it can be retrieved through recognition, i.e. via the comparison of an incoming stimulus to existing memory traces. Recall is generally more difficult than recognition, since it requires retrieval of more features of a memory than the process of recognition, in which some feature is already available (see Haist, Shimamura, & Squire, 1992). Several theoretical models have proposed that recognition memory can be achieved through two different processes (dual-process models), that correspond to the subjective experience of an item as being either *remembered* or *known*. Whereas Tulving (1985, 1993) attributed these two experiences to episodic vs. semantic memory, Aggleton and Brown (2006) use the terms *recollection* and *familiarity* (see Yonelinas, 2002 for a review). In their terminology, recollection corresponds to the episodic memory and the experience of remembering an event, whereas familiarity consists in knowing that something is familiar without being able to retrieve the specific experience. Opponents of the dual-process models, however, argue that remember-know judgments of recognition are the products of different levels of confidence. Confidence, in turn, depends on the strength of the memory trace, with differences in strength being on a continuum rather than at two distinct levels (Dunn, 2004).

The arguments for positing distinct processes as underlying different forms of recognition memory rely on models of how different brain structures contribute to memory experiences. There is consensus that declarative memory in general is dependent on structures in the medial temporal lobe, primarily the hippocampus. The hippocampus receives input from many different cortical areas involved in the perception of an event, and is able to bind together different aspects of the experience

into a full memory representation. Therefore, the hippocampus is critical for learning arbitrary associations between items, which is the fundamental nature of both episodic and semantic memories. A further development of the original dual-process theories (Yonelinas, 2002) is a three-component model referred to as the *binding of item and context (BIC)* model (Diana, Yonelinas, & Ranganath, 2007; Eichenbaum, Yonelinas, & Ranganath, 2007). This model rests on imaging data showing that *remember* judgments, i.e. recognition involving recollection, are associated with activity in the hippocampus and the parahippocampal cortex. In contrast, recognition based on *familiarity* is supported by the perirhinal cortex, one of the structures surrounding the hippocampus. This is because the rhinal cortex receives input from neocortical areas that process individual items or objects (the 'what' stream), and its neural activity is modulated by novelty or repetition of these items. This information about the novelty value of a single item is sufficient to enable a memory experience of familiarity. The parahippocampal cortex receives input from the 'where' stream of visual processing, which provides the context of an experience. These two types of information are then transferred to the hippocampus where they are combined into a unified episodic memory experience. According to the multiple-process models of recognition memory, the critical aspect of episodic memory is the availability of both item and context information in the memory representation. Thus, the subjective awareness emphasized by Tulving is considered peripheral, which enables the phenomenon to be studied in subjects that are incapable of introspective report (e.g. animals and infants). However, Diana et al. (2007) propose that recollection of item-item associations should also be dependent on the hippocampus, since this part of the brain is needed to link one item to another. This is especially relevant to the formation of semantic memories, which are defined in terms of their lack of context-specificity, yet still depend on establishing associations between different stimuli.

Memory for word meanings

The mechanisms involved in accessing declarative memories are important if we are to understand the processes of word comprehension and production, and the mechanisms involved in forming declarative memories are of course crucial in understanding how we learn the meanings of words. When we know the meaning of a word its meaning is stored as a semantic memory - general abstracted knowledge. We don't re-experience a specific event every time we hear or use a familiar word. Yet in the process of learning words, the experience of hearing a new word and inferring its meaning is a specific individual experience like any other, i.e. episodic in nature. The *Complementary Learning Systems* (CLS) theory of declarative memory presents an account of how such individual learning episodes are linked to generalized semantic knowledge (McClelland, McNaughton, & O'Reilly, 1995; O'Reilly, Bhattacharyya, Howard, & Ketz, 2011; O'Reilly & Norman, 2002). As is generally accepted, this

model locates the task of fast and precise learning of arbitrary combinations of input, which results in distinct memory representations for items and episodes, in the hippocampus. To the extent that these representations are re-activated (through rehearsal, the re-experience of very similar events, or during sleep), the hippocampus trains the involved neocortical areas to develop a network based on general patterns, resulting in more overlapping representations. With time, this cortical network functions independent of the hippocampus. The neocortical system represents abstracted semantic knowledge aggregated across many experiences, as is the nature of memories of lexical items and their meanings. Our knowledge of what a cat is contains information about what a cat looks like, how it sounds and how soft its fur is, as well as a host of facts. This knowledge can most likely be accessed without involvement of the hippocampus. But the first time we ever encountered a cat (whether a real or fictional one) and heard it labelled with the novel word 'cat', the hippocampus would need to bind the encoded object with the encoded word, and after only one such learning experience the hippocampus would be activated in order to retrieve the meaning of the word (word comprehension), or in order to actively label a cat upon our next encounter (word production).

An account of how the processes of word learning map onto the CLS theory has been presented by Davis and Gaskell (2009). As was proposed above, they argue that new words are initially encoded as episodic memories by the medial temporal lobe. After multiple encounters with words and their referents consolidation processes form stable cortical representations independent of the hippocampus. In particular, they emphasize the role of sleep in consolidation, and describe how the integrative effect of sleep on hippocampal memories changes the nature of word representations. The authors present both behavioral and neuroimaging data supporting a CLS model for word learning. For instance, they argue that lexical competition effects of newly learned words on pre-existing words in the lexicon emerge during the course of several days due to consolidation by sleep, indicating that it takes some time before the novel words are integrated into the lexicon. This is despite constant good performance on recognition tests of the individual novel words from soon after training until several days later (e.g. Dumay & Gaskell, 2007; Dumay, Gaskell, & Feng, 2004; Gaskell & Dumay, 2003). In addition, Davis and Gaskell (2009) review neuroimaging data consistent with the proposed view that the hippocampus is involved in the initial learning of novel words and their meanings, while changes in cortical responses emerge later. For instance, fMRI data collected while subjects learn spoken pseudowords paired with pictures has shown a linear decline in left hippocampal activity across five learning presentations of consistently paired pseudowords, but no change in activity to inconsistently paired pseudowords and pictures (Breitenstein et al., 2005). A greater such decline in activation also predicted better memory for the word-picture mappings. In contrast, a comparison between the processing of real familiar words and novel pseudowords showed differential responses in cortical

regions involved in word processing, including the superior temporal gyrus, shortly after training, while after a 24 hour delay the same regions did not differentiate between the two word types (Davis, Di Betta, Macdonald, & Gaskell, 2009). Importantly, the CLS model of word learning proposes that the cortical route to learning is active all the time along with encoding through the hippocampus (i.e. it does not only depend on consolidation via the hippocampus). However, the learning that takes place without involvement of the hippocampus (demonstrated by studies in amnesiacs with medial temporal lobe damage) is thought to be much slower (i.e. it requires many more repetitions), and less flexible than the cortical representations that result from consolidation via the medial temporal lobe (e.g. Bayley & Squire, 2002; Gardiner, Brandt, Baddeley, Vargha-Khadem, & Mishkin, 2008).

The research reviewed so far highlights the important role of the medial temporal lobe, and particularly the hippocampus, in the early stages of word acquisition in adults. In addition, it has recently been argued that the hippocampus is also critical for the online processing of language by contributing to the ability to rapidly and flexibly integrate multiple sources of information, during both language comprehension and production, such as handling the relations between different parts of an utterance (Duff & Brown-Schmidt, 2012; Kurczek, Brown-Schmidt, & Duff, 2013).

Development of declarative memory

This account of how declarative memory, which includes the memory for word meanings, involves the medial temporal lobe, raises the question whether these brain structures are sufficiently developed in infancy to support the formation of declarative memories in the same way as in adults. The fact that few adults have access to any memories formed during the first two to three years of life (referred to as 'infantile amnesia') has led many to believe that infants and children are indeed unable to form declarative memories. The criterion of conscious awareness and mental time-travel (Tulving, 1993), for which it is difficult to find evidence in pre-linguistic infants, has further contributed to the idea that infants' memories are different from those of adults, and essentially non-declarative in nature.

Although the hippocampus is not a fully mature structure at birth, several parts of the hippocampal region develop early. The entorhinal, perirhinal and parahippocampal cortices are adult-like and functional at birth (Alvarado & Bachevalier, 2000). The dentate gyrus undergoes more development postnatally, particularly during the first year, although it is not as immature at birth as was once assumed based on findings showing a very immature dentate gyrus in newborn rats (Seress, 2001). Studies on rhesus macaques have confirmed a relatively protracted development of the dentate gyrus, while other hippocampal regions, e.g. CA1, CA2, and the subiculum, that

receive input from the entorhinal cortex, develop early (Lavenex & Banta Lavenex, 2013). The changes that occur in the dentate gyrus during infancy have been taken as support for a *neuromaturational* account of memory development, which proposes a qualitative shift in the nature of memory representations during the first year. According to this account infants have an early non-declarative, or pre-explicit, memory system that functions from birth, and a late adult-like declarative system that begins to function toward the end of the first year (e.g. Bauer, 2006; Nelson, 1995). The early system is thought to rely on structures outside of the medial temporal lobe, supporting non-declarative memory in adults, as well as the early developing parts of the hippocampal regions (Richmond & DeBoer, 2006). One important difference between these types of memory and those formed later in infancy is that they lack flexibility, presumably because different aspects of an experience, such as items, actions and context, are encoded as a unitary representation. The dentate gyrus is suggested to play an important role in supporting flexible integration of different parts of an experience, which for instance allows memory retrieval in contexts not identical to those originally encoded (Eichenbaum, 1997; Richmond & DeBoer, 2006). Other researchers argue that there is a gradual improvement in declarative memory ability during infancy, with both non-declarative and declarative memory systems being available from birth (Hartshorn et al., 1998; Rovee-Collier, 1997). Gradual improvements during infancy on tests thought to tap declarative memory, such as the deferred imitation paradigm, have been interpreted as support for such a continuous development (Jones & Herbert, 2006).

In particular, infants' impressive ability to learn arbitrary associations from experience already from birth has been referred to as evidence against the existence of two qualitatively different memory systems. In a review, Rovee-Collier & Giles (2010) described early infancy as a period of "exuberant learning", meaning that infants rapidly and fairly non-selectively learn associations between co-occuring stimuli and events. They argue that young infants actually learn more from an experience than adults, because they are less selective in which associations are formed. Excessive associations are then eliminated by rapid forgetting and extinction. Importantly, the authors are critical of the neuromaturational account of memory development, and argue that this early associative learning cannot be attributed to non-declarative memory processes. They review evidence from several different learning tasks that show that infants' memories are not as inflexible and limited as is predicted by a non-declarative memory system. For instance, the context-specificity that is often found in tasks involving the learning of object-action sequences (kicking to move a mobile, or a deferred imitation task) can be overridden by pre-exposing the infant to two different contexts (Barr, Marrott, & Rovee-Collier, 2003; Boller, 1997). Young infants are also able to form associative chains between stimuli that are physically present at the same time (Cuevas, Rovee-Collier, & Learmonth, 2006). Rovee-Collier and Giles (2010) seem to view memories formed in early infancy as qualitatively similar to adults'

memories based on arbitrary associations, with the fundamental difference that infants are less selective and therefore remember other things than adults. They suggest that a shift in selective attention and a subsequent decrease in exuberant learning occurs around 9 months, which is the same age at which the explicit memory system emerges according to the neuromaturational account. The authors do not specify which structures and mechanisms in the brain might underlie the exuberant learning in early infancy; instead they focus on describing the nature of the memories formed during infancy, and emphasize their similarity to adult declarative memories. Nevertheless, they conclude the article with the suggestion that infants' associative learning is based on *fast mapping*, a process thought to support infants' early word learning. As previous researchers have suggested before (Markson & Bloom, 1997), they argue that fast mapping is a general learning mechanism rather than a process of linking words to their meanings specifically. In the next section, I will more thoroughly describe and review research concerning the phenomenon of fast mapping.

As a parallel to the idea that infants' memory abilities are best characterized by a gradual improvement and development, Wojcik (2013) describes infants' word learning ability during their first years as being related to changes in domain-general memory abilities. Specifically, the focus is not on different memory systems, but on changes in the different processes involved in most long-term memory formation, namely *encoding, retention, consolidation* and *retrieval.* An important finding is that infants encode information faster as they grow older. Evidence for this has primarily been taken from research using habituation paradigms. After repeated exposure to a stimulus, infants show a novelty preference when presented with novel stimuli compared to the trained stimuli, but only if they have successfully encoded the original stimulus. Older infants need less exposure in order to show a novelty preference (Wojcik, 2013). This is likely to affect word learning as well, but there do not seem to have been systematic studies of how much exposure infants of different ages need when learning novel word meanings. Increases in encoding speed for visual stimuli have been explained by improvements in attention processes (Colombo, 2001). It has been shown that 2-year-olds learn novel words for objects better during explicit labelling than when they have to infer the referent from an ambiguous context (Horst & Samuelson, 2008). This indicates that making a word-object association more salient improves encoding, and could mean that younger infants may achieve better encoding if offered more support for their attention.

The ability to retain memories over a certain period of time has also been shown to improve continuously during the first two years of life, with an increase from only one day to several weeks. This has been demonstrated by performance in operant reinforcement and deferred imitation paradigms (Hartshorn et al., 1998; Jones & Herbert, 2006). It has been argued that word learning studies with infants rarely assess retention of newly learned words, even over short periods of time (Horst &

Samuelson, 2008; Wojcik, 2013). However, by measuring event-related potentials (ERPs) in a word-object mapping paradigm, studies have shown that 14-month-olds retain knowledge of word-referent mappings after a one day delay, while 6-month-olds only demonstrate such learning during the actual learning experience but not one day later (Friedrich & Friederici, 2008, 2011). By comparison, Carey and Bartlett (1978) demonstrated that 3-year-olds had knowledge of a novel word one week after a very brief, indirect exposure. Although the study by Friedrich and Friederici (2008) did not include a follow-up to see whether the 14-month-olds retained this knowledge even longer than a day, these results indicate that the retention of word meanings improves with age. Such improvements can theoretically depend on either changes in the quality of encoding or changes in consolidation processes. Bauer and colleagues have argued that individual differences in consolidation processes over a 1-month-period can account for performance on deferred imitation tasks in 9-month-olds. In their studies, ERPs measured during a test-session 1 week after training predicted behavioral performance after 1 month, but not ERPs immediately after training (Bauer, Wiebe, Carver, Waters, & Nelson, 2003; Carver, Bauer, & Nelson, 2000). Results of encoding were inferred from performance on the immediate test, while measures after a 1-week delay were seen as a result of consolidation. Finally, it has been shown that retrieval of memories, through reactivation, positively influences further retention by strengthening the memory (Barr, Rovee-Collier, & Campanella, 2005; Rovee-Collier, Hartshorn, & DiRubbo, 1999). However, it is unclear how the actual retrieval process develops during infancy.

Fast mapping

Fast mapping is a term that was first used by Carey and Bartlett (1978) to describe the fact that three- to four-year-old children were able to map the novel color-word "chromium" to an olive-colored object, in an indirect labelling context that contrasted the word with a known word, i.e. "Bring me the 'chromium' one. Not the red one, the 'chromium' one." (Carey & Bartlett, 1978, p. 18). Since then, fast mapping has been used to refer to the more general phenomenon of young children's ability to form a word-referent association from minimal exposure. Studies involving either ostensive labelling, or indirect inference from sentence contexts or contrast with familiar words, or a mixture of these conditions, have shown that infants from around 1 year of age are able to link a word to its referent based on very few exposures (e.g. Schafer & Plunkett, 1998; Werker, Cohen, Lloyd, Casasola, & Stager, 1998; Woodward, Markman, & Fitzsimmons, 1994).

The ability to quickly map a word onto its referent (fast mapping), a purely receptive ability, has been suggested as one factor contributing to the productive vocabulary spurt at the end of the second year (Friedrich, 2011). However, the fact that children are capable of fast mapping already at the age of one calls into question whether there

is a direct link to the vocabulary growth that typically takes place after 18 months. There is even evidence that infants as young as six months are able to form associations between objects and words after four learning trials, although they do not retain these associations one day later (Friedrich & Friederici, 2011). As has already been mentioned, some researchers believe that fast mapping may not be a specific word learning mechanism, but a general process through which infants form associative memories. On this view, fast mapping may account for the extensive data outside the word learning field showing that young infants can form declarative-like associative memories. If this is accurate, so that we can conclude that children as young as six months can learn words through fast mapping, it seems that productive vocabulary growth around 18-24 months cannot be explained by the sudden emergence of fast mapping abilities. However, it is possible that there is a gradual improvement in all the abilities supporting the formation of memories through fast mapping, such as more efficient encoding, improved attention that highlights what it is to be encoded, and improved consolidation, all of which would improve retention. These improvements may need to reach a certain level before a child is likely to start producing a large number of words. For instance, a study of 'late-talking' toddlers, those who are at the lowest end of the productive vocabulary distribution, showed that these children are significantly worse than their normal-talking peers at novel word learning through fast mapping, both in terms of comprehension and production of the novel words. Performance on the fast mapping task at 30 months also predicted certain language skills at age 5 ½ (Ellis Weismer, Venker, Evans, & Moyle, 2013). Similarly, using eye-tracking measures during a fast mapping task, a recent study indicated that 18-month-old late talkers were less confident about the newly learned word-object associations than their normal-talking peers (Ellis, Borovsky, Elman, & Evans, 2015).

Despite much research on fast mapping in children of different ages, it remains unclear what exactly it is that children learn by fast mapping (discussed in e.g. Bion, Borovsky, & Fernald, 2013). The term 'fast mapping' has been used to describe quite different processes. Often it is used to describe online disambiguation, i.e. the ability to determine what a word refers to. Experimental paradigms often create an ambiguous situation with two possible referents for a word, but by for example letting one of them be an object for which the child already knows a word, the child can infer that that the novel word refers to the novel object. According to this approach, the ability to fast map actually only refers to the ability to figure out what a novel word refers to in a given situation. This referent-selection may or may not lead to actual word learning, in the sense that the association between the novel word and its referent is remembered after a delay, either short or long. When discussing the importance of developing fast mapping abilities, it is often assumed that this referent-selection leads to better word learning. And of course this is a pre-requisite of some sort, because it must be difficult to remember a word's meaning if one has not even

figured out which of several possible things the word refers to. But it is also possible that children are quite good at this online referent-selection at an early age, but still are poor at actual word learning, and in that case this form of fast mapping would not be the most interesting mechanism for understanding the development of word learning. One computational model of word learning emphasizes the distinction between these two concepts, where fast mapping (conceptualized as referent selection) is an online behavior that can be separated from actual learning which is the result of associative learning over time (McMurray, Horst, & Samuelson, 2012).

A different perspective on the term fast mapping is that it involves actual learning of word-referent associations. In this sense, it is of less importance whether the learning situation involves referent ambiguity or direct, ostensive labelling, such as showing a picture of an object and saying "this is a wug". If the child after one or several such word-referent pairings shows any evidence of knowing what the word refers to, it is considered to have achieved successful fast mapping. This is the approach adopted by studies using electrophysiological measures of fast mapping. In these paradigms, pictures of novel objects are presented along with a novel word, and the picture-word pairings are repeated a number of times. After this, the same objects are presented with incorrect, though equally familiar, words and an ERP response that differentiates these incongruous pairings from the congruous pairings is used as an indication that the child had formed an association between the specific object and word (Friedrich & Friederici, 2008, 2011; Torkildsen et al., 2008). A similar approach of direct word-object pairing has been used along with preferential looking measures of word learning, where a longer looking time to incorrect pairings is taken as an indication of successful fast mapping (Schafer & Plunkett, 1998). The difference between this view of the fast mapping mechanism and the referent-selection view is that this view emphasizes the actual establishment of an associative memory representation. Even if such a representation is not retained after a delay outside the frame of the learning experiment, the measures involving responses to incorrectly paired words and objects demonstrate that an associative link has been encoded. Only this latter view of fast mapping is compatible with the hypothesis that it is a general learning mechanism for forming associative memories.

Whether fast mapping is seen as a mechanism of forming quick associative links between a word and its referent, or only the online disambiguation of word referents, the question remains of how the information learned from fast mapping is, or is not, retained. It has been argued that there is a substantial discrepancy between the ability to infer a referent to a novel word, and the retention of any knowledge of the word (Bion et al., 2013; Horst & Samuelson, 2008; Horst, Scott, & Pollard, 2010). Horst and colleagues showed that 24-month-olds, although proficient at referent selection, were very poor at retention even after only a 5-minute delay (2008). Retention was however improved if the novel objects were also ostensively labelled. Similarly, Bion et al. (2013) showed that when exposed to novel words in ambiguous situations, 18-

and 24-month-olds did not retain an association between the word and the object (retention trials were immediately after training), although the 24-month-olds were capable of actual disambiguation. Only 30-month-olds showed minimal (just above chance) retention of the word-object association after learning from ambiguous situations. At 18 months, children were not capable of online disambiguation either, but did show retention of words learned through unambiguous, ostensive labelling. Interestingly, this experiment included only two novel words to be learned, i.e. the learning demand must be considered low, and still the children showed such poor retention even after a minimal delay. Importantly, however, these studies show that situations involving explicit labelling and ambiguous referent selection have different consequences for word learning, and that explicit labelling facilitates learning in young children. It has been argued that this effect is due to the presence or absence of competitive objects that interfere with attention, and that other aspects that increase attention to the correct object in ambiguous situations also can enhance learning (Axelsson, Churchley, & Horst, 2012; Horst et al., 2010). The difference in outcome following ambiguous or unambiguous word mapping most likely explains why most studies that claim to show fast mapping in very young children (around 1 year) have used explicit labelling paradigms (Friedrich & Friederici, 2008; Schafer & Plunkett, 1998; Werker et al., 1998; Woodward et al., 1994). Although most of these studies only test established associations immediately after training, this paradigm has shown retention of associations at least one day later for 14-month-old infants (Friedrich & Friederici, 2008).

Even though many studies have shown that infants are capable of rapidly forming associations between words and objects, it has been questioned whether such an associative link constitutes real "word learning", and not only with regard to retention. For instance, Werker et al. (1998) discussed whether there is a difference between the knowledge that a word and an object "go together", and an actual referential understanding that a word means, "stands for" the object.

Fast mapping and the brain

The research reviewed above on fast mapping abilities in children does not address the question of what mechanisms in the brain are involved in the process. Recently, several studies on adults have explored whether there is a fast mapping mechanism for learning that enables memory formation independently of the hippocampus. As was discussed in the section on the Complementary Learning Systems account of declarative memory, there is a common view that there is both a cortical and a hippocampal route to learning, but information that is encoded only through the cortical route leads to slow, inflexible learning. When cortical networks are 'trained' by the hippocampus memory representations are generalized and flexible, but this consolidation process also takes time. In other words, this model does not support the

idea that declarative memories can be learned quickly through only cortical activations.

In a study involving amnesic patients with hippocampal damage, learning outcomes from two different tasks were compared, designed to involve either explicit memorization dependent on the hippocampus or incidental learning from context, referred to as 'fast mapping' (Sharon, Moscovitch, & Gilboa, 2011). The standard associative learning task was to try to remember a novel label for a novel animal displayed in a picture (e.g. a 'numbat'). The fast mapping (FM) task on the other hand, showed a picture of a novel animal alongside a picture of a familiar animal, and the task was presented as purely perceptual, to answer a descriptive yes/no question (e.g. "Is the numbat's tail pointed up?"). Thus, a key difference between the tasks was that in the FM task learning was not deliberate, rather was a bi-product of having to solve another task. Learning was assessed in a recognition test 10 minutes later, and one week later, with a forced-choice procedure, where the participant had to select an object among two distractors that corresponded to a target label. The results showed that patients with severe hippocampal damage were able to learn the novel labels from the FM task, but not from the explicit learning task, and actually performed as well as the control participants in the FM task. While healthy controls learned better from the explicit associative task, the amnesic patients performed at chance level. The study also included two patients with lesions to the left temporal pole of the neocortex along with either intact or partly intact hippocampal region. These two patients were unable to learn from the FM task. The authors concluded that semantic knowledge of arbitrary associations can be learned independently of the hippocampus, probably involving the anterior temporal cortex and possibly supported by structures in the parahippocampal cortex, such as the left perirhinal and entorhinal cortices. This conclusion introduces the possibility that infants' fast associative learning might also be supported by these cortical regions, that are functional and mature earlier than the hippocampus (Alvarado & Bachevalier, 2000).

There are few studies investigating this phenomenon, and attempts to replicate and extend the findings by Sharon et al. (2011) have yielded conflicting results. Two studies using similar procedures found that amnesic patients were not able to retain any associative knowledge from a fast mapping task, although they were able to perform the fast mapping online (Smith, Urgolites, Hopkins, & Squire, 2014; Warren & Duff, 2014). Thus, it is still unclear whether the suggested cortical route for fast associative learning will find adequate empirical support. However, other researchers than Sharon and colleagues agree that there is reason to believe such fast neocortical learning is possible (e.g. Shtyrov, 2012), and refer especially to electrophysiological data demonstrating changes in cortical responses after only brief exposure to novel words (Borovsky, Kutas, & Elman, 2010; Mestres-Misse, Rodriguez-Fornells, & Munte, 2007; Shtyrov, 2011; Shtyrov, Nikulin, & Pulvermüller, 2010). One recent study employed a design contrasting explicit

encoding and fast mapping (incidental encoding) of novel word meanings in healthy adults (Coutanche & Thompson-Schill, 2014). The results demonstrated that while explicit encoding formed strong distinct memories without lexical competition with existing vocabulary, the fast mapping task produced word representations that seemed immediately integrated into the existing 'mental lexicon', showing effects of lexical competition both immediately after learning and one day later. The authors also concluded that the critical element of this fast mapping mechanism is the contrast between novel and familiar items during learning.

The studies investigating fast mapping processes in adults emphasize the critical contrast between explicit encoding, where we consciously try to remember something, and the incidental nature of learning through fast mapping. It is almost as if we need to fool the hippocampus by pretending that there is nothing to be memorized in order for it to relax and let the cortical route to learning take over. When fast mapping in children is described, however, both incidental learning from context and more explicit labelling is incorporated by the concept. If we imagine a toddler's natural word learning environment, there is of course a mixture of these types of input. Children pick up word meanings both from continuous speech using many different cues to figure out a referent, and from explicit labelling, for example when a parent pointing says "Look! A dog!". Even if these two situations may induce different memory mechanisms in adults, that is not necessarily the case for young children. Infants are probably not consciously aware of deliberately trying to remember the label "dog", in the way that adults participating in a memory experiment are. Also, if the hippocampal structures supporting explicit encoding in adults are not fully functional in infants and toddlers, the cortical fast mapping route might have precedence, or be the standard learning route, in infants regardless of the form of input. In other words, the experimental tasks used when investigating infant fast mapping abilities might not be as restricted as with adult participants. It is reasonable to believe that the many experiments using explicit labelling do not induce different memory mechanisms in infants than those using incidental learning, although the type of input may very well affect the difficulty of the task, and thus have an effect on the success of learning. The bottom line is, however, that we do not actually know which brain structures are responsible for infants' and young children's ability to quickly learn arbitrary associations between stimuli. In order to gain that knowledge, it would be necessary to perform controlled learning experiments on young children while using brain imaging techniques with good spatial resolution, such as functional magnetic resonance imaging (fMRI), and due to practical difficulties this has hardly been done (for a discussion, see Wojcik, 2013).

Word processing in the brain

Although the previous sections have focused on general memory mechanisms involved in word learning, there are regions and processes in the brain that are especially important in handling linguistic input. After a relatively brief overview of critical brain regions in the so-called "language network", and their roles in the different stages of language processing, I will move on to describing event-related potential measures of word processing that are especially relevant to this dissertation.

The language network in the brain

Since the natural modality of language is auditory (as opposed to visual as in reading and writing, or in sign language), this overview of language processing will be restricted to processing of speech. A highly influential model of speech processing in the brain is the "dual stream model" proposed by Hickok and Poeppel (2007). This model is displayed in figure 3. According to this model there is a ventral stream, involving structures in the superior and middle parts of the temporal lobe, that processes incoming speech signals for comprehension. In addition, there is a dorsal stream with an auditory-motor integration function, which reaches from posterior dorsal parts of the temporal lobe to posterior parts of the frontal lobe. This stream translates auditory speech signals to articulatory motor representations. The dorsal stream is thought to be strongly left lateralized while the ventral stream involves both hemispheres. Incoming speech sounds are first analyzed in the auditory cortices bilaterally, and then move on to phonological-level processing in posterior and middle parts of the superior temporal sulcus (STS). After this the information follows the two processing streams, which work in parallel. In the ventral stream the information is passed on to the so-called "lexical interface", in the posterior parts of the middle temporal gyrus and inferior temporal sulcus, which links the phonological and lexical items to semantic information. The semantic representations, however, are stored throughout the cortex. The dorsal stream has been described as especially important for language development, because it provides the link between sensory speech input and articulatory functions that need to be trained to produce the same sounds. It is also proposed that it provides the basis for phonological short-term memory. Thus, this pathway is important for the ability to maintain a speech segment in working memory and attempt to reproduce it, something that children need to do a lot when learning new vocabulary.

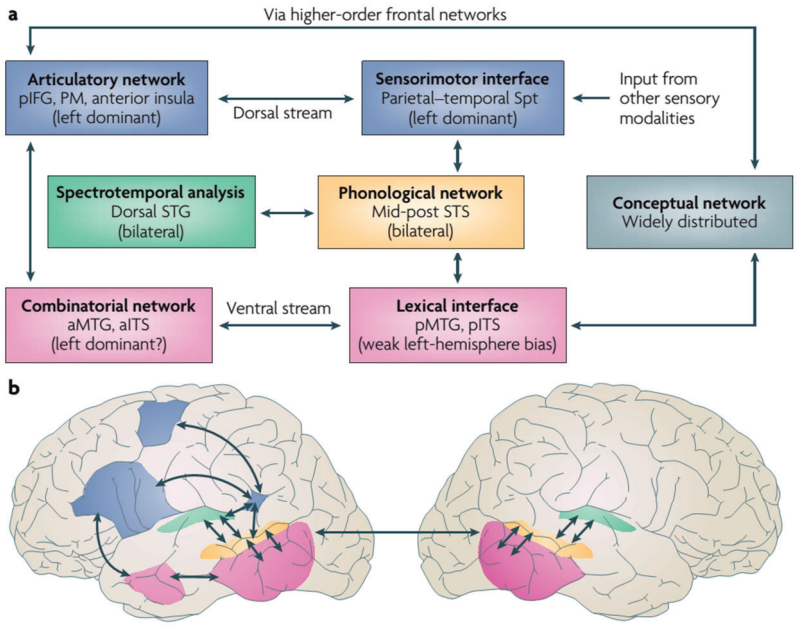

Figure 3. The dual-stream model of the functional anatomy of language (Hickok & Poeppel, 2007). Reproduced with the permission of Nature Publishing Group.

An extension of the original Hickok and Poeppel (2007) model was recently proposed, where it was suggested that there are two separate dorsal pathways, and two separate ventral pathways (Friederici & Gierhan, 2013). One dorsal pathway connects areas in the temporal cortex (TC) to the pre-motor cortex, supporting speech repetition as was described above. The other connects the TC to posterior parts of Broca's area, and supports complex syntactic processes. Ventrally, the TC is connected to the frontal cortex through the fiber tracts called the uncinate fasciculus (UF) and the inferior-fronto-occipital fasciculus (IFOF). The IFOF is thought to be involved primarily in semantic processing (where parts of the frontal lobe have been shown to be involved in for instance categorization or lexical-semantic access), while the UF is thought to support basic syntactic processing. It seems that the ventral streams and the dorsal stream that connects to the pre-motor cortex mature early in development, and are already in place at birth. In contrast, the second dorsal pathway, involved in complex syntax processing matures much later (Brauer, Anwander, Perani, & Friederici, 2013). However, although fMRI data also shows that many of the same regions that respond to speech in adults are also active in the newborn brain, newborns differ from adults in that they have stronger inter-hemispheric connections than intra-hemispheric connections. With increased experience with language, the connections in primarily the left hemisphere between different regions involved in speech processing grow stronger (Perani et al., 2011).

ERP measures of word processing

Measuring event-related potentials allows for the monitoring of events in the brain as spoken words are being processed. The electroencephalogram (EEG) measures changes in electrical potential at the scalp, which reflect postsynaptic potentials of large groups of neurons firing in synchrony, primarily pyramidal cells located in the neocortex (Luck, 2005). By averaging sections of the EEG that are time-locked to a specific stimulus, it is possible to isolate specific patterns of potential change associated with different cognitive processes, referred to as event-related potentials (ERPs). An ERP component refers to a specific deflection of an ERP waveform that is selectively modulated by a certain task or event. There are a number of ERP components related to the brain's processing of language stimuli, and this review will be limited to those that are relevant to single word processing specifically, thus leaving out those related to processing sentences and syntax.

The N400 component. The most important ERP component to the topic of word meaning acquisition is the N400. It is a negative deflection that is typically largest over centro-parietal sites, occurring approximately 400 ms after stimulus presentation, and can be elicited by a range of meaningful stimuli but most commonly by words (for reviews, see Kutas & Federmeier, 2011; Lau, Phillips, & Poeppel, 2008). It was first discovered by Kutas and Hillyard (1980) as a response elicited by words creating a semantic violation in sentences, e.g. "He spread the warm bread with *socks.*". Since then the N400 has been demonstrated in many different experimental settings; in response to single words preceded by semantically unrelated compared to related words, to words presented in written form or aurally, and even to other meaningful stimuli such as pictures (Barrett & Rugg, 1990). Importantly, the N400 is considered a normal response to a word, but its amplitude is attenuated when there is some way of predicting or expecting the word from the context, and in contrast its amplitude is larger the more unexpected the word is.

The N400 is specifically modulated by changes in semantic expectedness, not other types of unexpected events or anomalies. It is not, for instance sensitive to physical anomalies such as a larger font, or to syntactic errors such as "leg" instead of "legs" (reviewed in Hillyard & Kutas, 1983). Also, it is not only sensitive to semantic anomalies but to the general predictability of a word based on the preceding context. Thus, in a sentence that is perfectly semantically valid but where a specific word is not easily predicted, i.e. there are many reasonable possibilities, the word will elicit a larger N400 than the same word would in a more restricted sentence context that creates a specific expectation (Kutas & Hillyard, 1984). Similarly, violations to a person's world-knowledge also elicits an N400 effect, such as when a Dutch person reads "Dutch trains are *white* and very crowded" when in fact the person knows that they are yellow (Hagoort, Hald, Bastiaansen, & Petersson, 2004). This type of

violation elicited an N400 of comparable amplitude as a pure semantic violation such as "Dutch trains are *sour* and very crowded", which simply does not make sense.

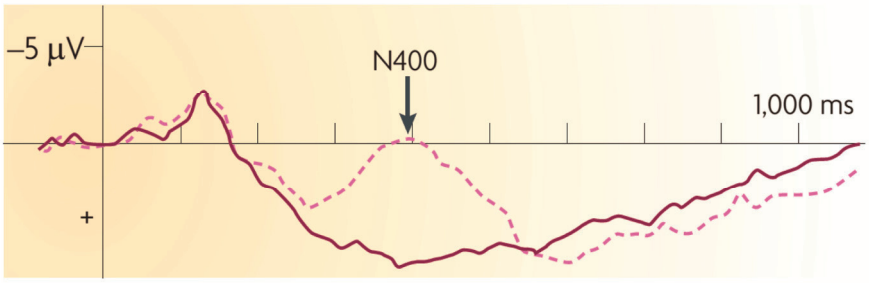

Figure 4. The standard N400 effect in a sentential context (Lau et al., 2008). Reproduced with the permission of Nature Publishing Group.

As is discussed in Lau et al. (2008) there are primarily two conflicting views of which cognitive process gives rise to the N400 component. According to the lexical integration view the N400 reflects the process of integrating the target word into the context. It is argued that this process occurs post lexical access, and is a combinatorial process of integrating the meanings of different parts of a context. In contrast, the lexical view argues that the N400 reflects the actual process of lexical access, and that the N400 effect (the smaller amplitude elicited by a related context) is due to facilitated access following activation of features of long-term memory representations that are associated with a lexical item. Critically, the N400 component is argued to arise from processes of access to long-term memory. Interestingly though, not only meaningful stimuli elicit an N400, but also pseudowords, stimuli that look/sound like real words but are not (Bentin, McCarthy, & Wood, 1985; Rugg & Nagy, 1987). Pseudowords are potentially meaningful, and the presence of an N400 suggests that the brain attempts to access a meaning even when there is none. In contrast, nonwords (phonotactically illegal strings of phonemes), that could not potentially be words, do not elicit an N400 (Holcomb & Neville, 1990). Lau et al. (2008) performed a meta-analysis of possible generators of the N400, and concluded that the posterior middle temporal cortex was the area most consistently activated. They argued that this supports the lexical access view since this area is associated with lexical access rather than integration mechanisms. However, they also acknowledge that the N400 measured at the scalp is most likely the result of many different processes located in different areas of the brain, contributing to different aspects of the semantic processing. In their review of the N400, Kutas and Federmeier (2011) reach a similar conclusion, that the N400 does not have one generator, rather can be thought of as a wave of activity starting around 250 ms after stimulus onset, probably

originating in the left posterior superior temporal gyrus, then spreading forward and ventrally and finally crossing over to the right hemisphere. There is also evidence that the rhinal cortex in the medial temporal lobe is involved in generating the N400 component (e.g. Meyer et al., 2005).

In addition to the most commonly studied 'N400 effect', which is the difference in amplitude between a semantically related and unrelated condition, the N400 component also undergoes a repetition effect. When the same word is repeated, the amplitude of the N400 decreases (Deacon, Dynowska, Ritter, & Grose-Fifer, 2004; Doyle, Rugg, & Wells, 1996; Petten, Kutas, Kluender, Mitchiner, & McIsaac, 1991). This effect enables the N400 to differentiate between old and new stimuli, thus indexing recognition memory. However, memory research has largely been performed separately from the N400 research, which has been regarded as a language area. Instead, a frontally distributed FN400 (typically elicited by visual stimuli) component has been considered to index the familiarity process of recognition memory, in contrast to the recollection aspect which has been associated with a later posterior positive deflection (e.g. Curran & Cleary, 2003). However, lately the distinction between the N400 and the FN400 has been questioned. It has been suggested that the FN400 in memory contexts indexes facilitated conceptual processing, either due to repetition or conceptual priming, and not a feeling of familiarity in general (e.g. Voss & Paller, 2006; 2007; but see Stenberg, Hellman, Johansson, & Rosén, 2009 for a different view). Furthermore, there is evidence from intra-cranial recordings and functional magnetic resonance imaging that the N400 and FN400 old/new effect rely at least in part on the same structures in the medial temporal lobe (Fernández & Tendolkar, 2006; Henson, Cansino, Herron, Robb, & Rugg, 2003; Meyer, Mecklinger, & Friederici, 2007; Meyer et al., 2005).

Since the N400 can provide information about semantic memory representations and the organization of semantic memory, it has proved a useful measure for investigating these aspects in infants. When language skills are limited and classic measures such as reaction time cannot be used, it is an advantage to be able to measure semantic processing in a passive subject. The first studies on the N400 in infants focused on establishing at which age the component first appeared and if it had the same characteristics as in adults. The first study that demonstrated an N400 effect at a very early stage of language development used a picture-word matching paradigm with words and objects commonly familiar to young children. The results showed that 19-month-olds produced a larger N400 component to incongruous pairings than congruous pairings, just like the adult comparison group, although the response started later than in adults (Friedrich & Friederici, 2004). Follow-up studies showed that the same effect was present in 14-month-olds, but not in 12-month-olds (Friedrich & Friederici, 2005a, 2005b) (though this finding has later been challenged, see below).

The picture-word paradigm was then adjusted so that it incorporated a learning phase and it was possible to present completely novel stimuli, pseudowords and pictures of novel objects, in order to examine the N400 in response to newly learned words. Using such a paradigm, it was shown that 14-month-olds produced an N400 effect to newly learned pseudowords after four learning trials, and the effect remained one day later (Friedrich & Friederici, 2008). In a similar paradigm with higher learning load, 20-month-olds with larger productive vocabularies produced such an effect, while those with smaller vocabularies only showed the effect for real, familiar words (Torkildsen et al., 2008). Other studies confirmed that the N400 effect can be associated with language skills, either productive or receptive vocabulary, or being at risk for developing a language delay or dyslexia (Friedrich & Friederici, 2006, 2010; Rämä, Sirri, & Serres, 2013; Torkildsen, Syversen, Simonsen, Moen, & Lindgren, 2007a). Furthermore, as in adults, it is larger for legal pseudowords than for real words, and is not elicited by illegal nonwords (Friedrich & Friederici, 2005b; Torkildsen et al., 2009).

The idea that the N400 component matures between 12 and 14 months has lately been challenged by new investigations in young infants. Junge, Cutler and Hagoort (2012) performed a similar picture-word matching experiment with 9-month-old infants and demonstrated that already at this age an N400 incongruity effect can be seen. They used real words and their referents, but also included a familiarization phase where each word was paired with its referent. In addition, they familiarized the infants with either the same exemplar of the word category (e.g. a cat), or with multiple exemplars (several different cats), and used novel exemplars when testing for the incongruity effect as well. Their results showed that the infants were able to generalize the word to novel exemplars, regardless of whether they had been given experience with one or several exemplars. The youngest age group to have demonstrated an N400 component is 6-month-olds, who in an experiment with novel pseudowords and objects showed a reduced N400 in the second half of the learning phase (Friedrich & Friederici, 2011). However, they did not produce an incongruity effect.

The N400 measure has also shown that young children's lexicons are categorically organized very early in development. For instance, the N400 incongruity effect is larger when a word is paired with a picture of something completely unrelated compared to something incorrect but semantically related (Torkildsen et al., 2006). Also, using a purely auditory semantic priming paradigm Torkildsen and colleagues demonstrated that 24-month-olds were semantically primed by related words and produced larger N400 amplitudes when words were preceded by unrelated words (Torkildsen, Syversen, Simonsen, Moen, & Lindgren, 2007b). This was confirmed recently in an experiment that also showed that only 18-month-olds with large productive vocabularies produced the same effect (Rämä et al., 2013). By measuring the N400 effect, a recent study was also able to demonstrate that sleep improves

infants' memories (9- to 16-month-olds) for specific word meanings, and enables generalization of word meanings to novel exemplars of a category (Friedrich, Wilhelm, Born, & Friederici, 2015). Thus, the N400 component is a powerful measure when investigating development of the lexicon and novel word learning. Unfortunately there is currently a shortage of longitudinal experimental studies of word learning using electrophysiological measures, but such an approach can potentially provide many new insights on the development of the ability to learn words and their meanings.

The N200-500 component. There is another, child-specific, component relevant to single word processing, which is often referred to as the N200-500 component. This is a fronto-laterally distributed negativity that is more negative to familiar words than to unfamiliar words (e.g. Mills, Coffey-Corina, & Neville, 1997; Mills, Coffey-Corina, & Neville, 1993). It is therefore interpreted as an index of word form familiarity or word recognition (for a review, see Friedrich, 2011). In accordance with this interpretation, it emerges and becomes more negative as a previously unknown word is repeated (Kooijman, Hagoort, & Cutler, 2005). It is also sensitive to the expectation of a word form, as it can be affected by priming from a relevant picture context. In these cases, the amplitude becomes more negative to congruous words (Friedrich & Friederici, 2004, 2005a). This is referred to as a phonological-lexical priming effect, as opposed to the semantic priming effect on the N400. Critically, it has been shown that children show effects on the N200-500 earlier in development than the N400, so that infants that do not yet produce an N400 incongruity effect may show a phonological-lexical priming effect, and show evidence of word recognition without mature semantic processing (Friedrich & Friederici, 2005b).

As with the N400, effects on the N200-500 component have also been related to measures of linguistic maturity, such as vocabulary size. For instance, 10-month-olds who produced an N200-500 response to words previously heard in continuous speech (a measure of word recognition based on word segmentation) had larger receptive vocabularies at 12 months and larger receptive and productive vocabularies at 24 months (Junge, Kooijman, et al., 2012). Similarly, 10-month-olds who showed a larger word familiarity effect when presented with continuous speech at both familiarization and test performed better at a "looking-while-listening" word comprehension test at 16 months (Junge & Cutler, 2014). Thus, the N200-500 component has proven a valuable measure of individual differences in word recognition and word segmentation abilities.

Although the N200-500 component is described as a response specific to infants and young children, it bears clear similarity to a component seen in adults as a response to familiarization of novel word forms. An early fronto-central negative component

(approx. 100 ms after the stimulus uniqueness point) has been shown to differentiate between known words and novel pseudowords (larger negativity to known words), and repetition of the novel pseudowords led to an increase in negativity resulting in a response similar to that elicited by the familiar words (Shtyrov, 2011, 2012; Shtyrov et al., 2010). In these studies, the pseudowords were not paired with a referent and thus did not create a semantic representation, thus the electrophysiological changes can be linked to learning of the word forms specifically.

Object Recognition and its Role in Early Word Learning

This dissertation focuses on the process of learning a specific class of words, namely object nouns. Learning object nouns requires forming a memory representation of both the word and the object it refers to, and linking these together. However, the process must go beyond linking two specific items together, since one must be able to generalize the word to novel exemplars of the object. This involves recognizing which objects 'go together', which is the process of categorization. To adults, seeing which objects are of the same kind usually seems straightforward, but an infant needs to learn certain strategies to determine how to categorize objects in its surroundings. It is easy to see that developments in abilities to recognize and categorize objects are relevant to the development of word learning.

The shape bias

One thing suggested to contribute to the ability to categorize objects is a phenomenon called the shape bias. The shape bias is the observation that children and adults tend to extend newly learned words to new objects based on similarity of shape rather than other perceptual features such as texture or size (Landau, Smith, & Jones, 1988). In the original study this bias was shown to develop with age, in that adults displayed a stronger bias than 3-year-olds, and 3-year-olds had a stronger bias than 2-year-olds. Older children use shape as a primary basis for categorization in general, while younger children tend to have a stronger bias in linguistic than in non-linguistic contexts. Children younger than 18 months do not systematically attend to shape in object categorization at all (Landau et al., 1988). Interestingly, attention to shape seems to increase with the size of the child's productive vocabulary, more specifically emerging around the point of 50 acquired count nouns (Gershkoff-Stowe & Smith, 2004). This is also the vocabulary size typically considered to be the threshold for the beginning of the vocabulary spurt (see Ganger & Brent, 2004 for a review and discussion). An intervention study demonstrated that explicitly teaching toddlers to attend to shape in object labelling situations improved their word

generalization skills and led to accelerated vocabulary growth (Smith, Jones, Landau, Gershkoff-Stowe, & Samuelson, 2002). According to the Attentional Learning Account (ALA) of the shape bias and word learning, experience with naming objects focuses attention on similarities in shape and leads to a general insight that objects are categorized according to shape. This, in turn, facilitates further word learning by making it easier to generalize from one object to another from the same category (Colunga & Smith, 2008; Smith, Colunga, & Yoshida, 2010; Smith et al., 2002). The reason that object shape is an especially relevant property for early word learning is that early vocabularies tend to be dominated by basic level object nouns, and basic level nouns are typically organized by shape (Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976). Recently, it was shown that the number of shape-based nouns specifically in a child's vocabulary, rather than overall vocabulary size, was positively correlated with the ability to remember a novel object's shape and the retention of the object's label (Perry, Axelsson, & Horst, 2015).

Although there is consensus concerning the existence of a shape bias, there are competing views about what underlies it and how it emerges. In a special section in Developmental Science (2008) proponents of two different perspectives on the shape bias presented their arguments. Critics of the ALA account argued that the shape bias is not primarily due to perceptual processes, formed by a gradual increase in attention to certain regularities in the environment. Instead, it is caused by children's conceptual knowledge about objects and word kinds (Booth & Waxman, 2008; Markson, Diesendruck, & Bloom, 2008). For instance, they emphasize the findings that sensitivity to object shape is not specific to labelling contexts but can also be seen in non-lexical object categorization tasks (Diesendruck & Bloom, 2003). Also, infants in the very beginning of word acquisition (well before 50 words) can also show a shape bias (Booth, Waxman, & Huang, 2005). Most importantly, they do not consider the shape bias an automatic mechanism but one that is influenced by conceptual cues (e.g. concerning object kind), so that children who are told that an object is animate take into account both shape and texture properties in noun generalization, while the same objects invoke a pure shape bias when children are told that they are artifacts (man-made) (Booth & Waxman, 2002). Essentially, the proponents of this *conceptual knowledge* perspective (not an official label) emphasize that the shape bias does not represent a unique word learning mechanism, but is one of many strategies for categorization that children learn depending on their conceptual knowledge of what kind of objects and words they are dealing with.

In response to this critique, proponents of the ALA account argue that they do not deny the involvement of conceptual knowledge in word learning and categorization. However, conceptual knowledge is not created by itself, but is connected to the perceptual processes that arise from children's experience, and that are shaped by a sensitivity to detecting regularities and correlations among events. They consider conceptual representations as simply another level of analysis, while the way to

understand children's cognition must go through analyzing the dynamics of the real-time processes of "perceiving, remembering, attending and acting" (Colunga & Smith, 2008, p. 195; Elman, 2008; Samuelson & Horst, 2008). The empirical evidence used to argue against the ALA account, such as the presence of a shape bias in non-lexical categorization tasks, is not considered detrimental to the theory. The shape bias is seen as especially relevant to word learning, and a verbal label interpreted as a noun is a strong cue that strengthens the shape bias, but this does not exclude the possibility of a shape bias in other non-linguistic contexts.

Object recognition based on shape or individual features

Recent studies on the shape bias have focused on the role of shape in more basic object recognition tasks that do not require learning a novel word. One study investigated whether 17- to 25-month-olds could recognize abstract shape caricatures of common objects (Smith, 2003). When dividing the sample into two groups based on productive count noun vocabulary size (under and over 100 words), it was found that although both groups recognized the typical versions of the common objects, only the large vocabulary group could recognize the abstract shape caricatures. This suggests that the shape bias is not only a phenomenon relevant to language learning, but may have to do with more basic object recognition processes.

In order to further investigate which perceptual processes are involved in such recognition tasks, Pereira and Smith (2009) conducted a study where the stimuli were systematically varied according to the presence of correct detail and appropriate shape. This time, 18- to 24-month-olds were divided into three groups according to vocabulary size. As in previous experiments, the highest vocabulary group was best at recognizing the objects that only had the appropriate shape and no local details. However, the children with the smallest vocabulary performed best when objects had the correct local details, regardless of the presence of appropriate shape. This group was significantly better than the large vocabulary group at recognizing such objects. This study adds to the understanding of the shape bias by showing two different approaches to recognizing objects, one based on global shape and one based on parts or local detail. The results are in line with an earlier study on infants' categorization of common objects with shared or different parts, as well as animal-vehicle hybrids. In this study, Rakison and Butterworth (1998) found that younger children (14-month-olds) attended more to salient parts or details, while older children (22-month-olds) took in information from whole objects and thus became more flexible in their approach to categorization. A follow-up study on the role of shape recognition and vocabulary also showed that two-year-old "late talkers" had a deficit in abstract shape recognition compared to typical controls (Jones & Smith, 2005). An extension of the research on shape caricature recognition was carried out in a study testing 18- to 30-

month-old children's ability to match a novel 2-part object to an identical exemplar among distracters that differed either in the shape of the object's parts but had the same spatial arrangement of parts, or that had the same part shapes but differed in spatial arrangement (Augustine, Smith, & Jones, 2011). The results showed that the children were better able to rule out distracters based on part shapes than on part relations. Thus, even though the correct object match was identical to the object presented only 15 seconds earlier, children found it very difficult to distinguish from other objects that had the same part shapes but different arrangement of the parts. This indicates that young children's object recognition is based more on the shape of specific parts than on the configuration between these parts. Finally, a study comparing shape caricature recognition and the shape bias in noun extension contexts demonstrated that developments in object recognition preceded the shape bias, suggesting that improved shape recognition ability plays a role in the development of a shape bias for word extension (Yee, Jones, & Smith, 2012).

In a related line of research, studies relying on infants' looking behavior (measuring habituation and dishabituation) have indicated that a shift from featural to relational visual processing takes place already between 7 and 10 months (Younger & Cohen, 1983, 1986). Although this is much earlier than the ages discussed in the shape bias/shape recognition literature, it is possible that different stimuli and different measures of performance (i.e. looking behavior vs. overt responses) capture different levels of competence concerning the same underlying processing (see Westermann & Mareschal, 2004; Younger, Hollich, & Furrer, 2004 for a discussion on the mechanisms involved). These studies also did not involve the labelling of objects or the task of novel noun generalization. Thus, it may be that the development of visual processing based on the configuration of individual features begins much earlier than we can observe a shape bias in children's behavior toward objects.

Visual processing in the brain

The *perception-action* model of visual processing is a highly influential model of how visual input is processed in the brain (Goodale & Milner, 1992; Milner & Goodale, 2008). According to this model, visual information follows two different streams of processing after initial input to the visual cortex, a ventral stream and a dorsal stream. For the purposes of object recognition, it is primarily the ventral stream, also described as the 'what'-stream that is relevant. In this stream the information is passed from visual cortices to the inferior temporal lobe where it connects to semantic knowledge about the visual content. The dorsal stream, on the other hand (the 'where'-stream), processes movement and action information.

Both individual features and their spatial relation are processed in the ventral stream, but at different points. Studies on the activation of individual neurons in macaque

monkeys suggest that visual processing is based on local contour fragments (e.g. specific orientation or angles) early in the ventral stream (V1, V2) (Ito & Komatsu, 2004), while further along the pathway in the inferotemporal cortex (IT) cells are activated by more complex combinations of features (Brincat & Connor, 2006; Tanaka, Saito, Fukada, & Moriya, 1991). Activation of individual features is faster and more immediate than the configural processing involving several features (Brincat & Connor, 2006). Although their findings are related specifically to the configuration of very simple features in posterior IT, Brincat and Connor argue that similar processes may occur further along the stream involving more complex parts. They suggest that very fast categorization of basic-level objects could rely on an early, nonconfigural categorization. One could speculate that such nonconfigural categorization would be more predominant early in development, and that the networks allowing for complex configuration of parts eventually give rise to the improved processing of global shape observed in children between 18 and 24 months.

Insights into the perception of object parts and their relations can also be provided by research on the condition of integrative agnosia. This is a type of visual agnosia where individuals seem to be able to recognize parts of objects but are unable to bind them into a unified whole (Behrmann & Kimchi, 2003; Behrmann, Peterson, Moscovitch, & Suzuki, 2006; Riddoch & Humphreys, 1987). In one experiment, a patient with integrative agnosia was presented with novel objects created by combinations of two geons, and was later given the task of recognizing the previously presented objects among different distractors (Behrmann et al., 2006). The subject was able to pick out the correct object among distractors that differed in one of the parts, but could not differentiate between the target and distractors that shared the same parts and only differed in spatial arrangement. The case of integrative agnosia provides clinical evidence for the differential processing of simple volumetric parts and the integration of parts into a whole object or shape.

Development of visual attention

A prerequisite for being able to process and recognize an object visually is that attention is directed towards the stimulus. Visual attention is generally inferred from looking duration, and changes in looking duration to different types of stimuli provide the foundation for one of the most influential research paradigms on infant cognition: the habituation paradigm. Visual habituation refers to the phenomenon that infants' looking duration decreases as a visual stimulus is presented repeatedly. When a novel stimulus replaces the repeated stimulus looking duration increases again, referred to as dishabituation or 'recovery of attention' (or if the two stimuli are presented side by side, infants look more to the novel stimulus). Habituation of looking duration is understood as a decline in attention as a stimulus becomes more familiar, while dishabituation indicates successful discrimination of the novel and the familiar stimulus (e.g. Kavšek, 2004). According to the most influential theory of habituation, *the comparator model*, a faster rate of habituation to a repeated visual stimulus is interpreted as more efficient visual encoding. When a stimulus is presented the infant starts to form a mental representation of the stimulus, which subsequently presented stimuli are compared to. Following repetition, the internal representation is updated to better correspond to the external stimulus, and as the two become more similar less time is required to process the visual stimulus. A large dishabituation response is thus thought to reflect good recognition memory for the old stimulus (see Kavšek, 2013 for a recent review and discussion of the comparator model). Developmental studies of visual attention generally show that overall looking duration to stimuli decreases with age over the first year, particularly between 2-6 months, although the pattern of change depends on the experimental paradigm (whether trials are presented with fixed duration or in an infant-controlled procedure) (Colombo & Mitchell, 2009).

These measures of visual attention in infancy have consistently been shown to relate to future language and cognitive skills (reviewed in Bornstein & Sigman, 1986; Kavšek, 2004; McCall & Carriger, 1993). Fundamentally, the rate of habituation of visual attention and strength of the dishabituation response in infancy are considered by many to be measures of a general information processing capacity that forms the basis for general intelligence. Before the developments in research on habituation it was thought that there was little stability in cognition measured in infancy, based on the poor predictive validity of standardized tests of development for future IQ. The moderately strong correlation between habituation measures and later IQ was taken as evidence for continuity in cognitive development throughout the lifespan (e.g. Bornstein & Sigman, 1986; Fagan & McGrath, 1981). One cognitive measure frequently found to correlate with infant visual habituation is vocabulary size in toddlerhood and childhood (Colombo et al., 2004; Kavšek, 2004; Tamis-LeMonda & Bornstein, 1989). Whether this correlation is mediated by general information

processing skills (some type of "g-factor") or whether there is a direct link between efficient visual processing and word learning is unclear. It does, however, suggest an interesting link between individual differences in processing of visual stimuli and individual differences in word learning ability.

ERP components related to object recognition

Although many visual ERP components, including early sensory components, are involved in object processing, this section will only cover later appearing components that necessarily involve some aspect of object recognition or identification, and that are useful when studying infant's object recognition abilities in particular.

The Negative Central component (Nc). The Negative Central (Nc) component is an ERP response found only in infants and young children, and it is not specific to object processing or to the visual domain. It is a negative deflection prominent over fronto-central regions peaking 400 ms after stimulus onset in 1- to 2-year-olds (later in younger infants) and is primarily elicited as a response to context-dependent novel, salient or interesting events (for a review, see de Haan, 2006). It is generally interpreted as an index of attention, where a greater amplitude reflects a higher level attention devoted to processing the stimulus (Courchesne, 1978; Courchesne, Ganz, & Norcia, 1981; Csibra, Kushnerenko, & Grossmann, 2008; de Haan, 2006; Richards, 2003). Richards (2003) showed that Nc amplitude was larger during sustained attention (measured behaviorally as a deceleration in heart rate) than during attention termination (heart rate returns to baseline). This amplitude difference was associated with individual differences in recognition memory, where infants showing a novelty preference during paired comparison task embedded in an oddball task were those who displayed a larger Nc amplitude during sustained attention (Reynolds, Courage, & Richards, 2010). The Nc component has been shown to differentiate between old and new stimuli, and this differentiation has been linked to behavioral measures of successful memory recall in deferred imitation tasks (Bauer, 2006; Carver et al., 2000; Heimann, Nordqvist, Rudner, Johansson, & Lindgren, 2013). Thus, a significantly larger Nc amplitude in response to previously presented objects compared to novel objects indicates object recognition. The amplitude of the Nc component has also been shown to decrease with object recognition, indicating an increasing familiarity with the stimulus (Junge, Cutler, et al., 2012; Nikkel & Karrer, 1994).

P400. The P400 component is a visual component seen at occipital electrodes, and that has traditionally been thought of as an infant version of the adult N170, a component specifically sensitive to face processing (de Haan, 2006). For instance, it differentiates between upright and inverted faces, with longer latency for inverted faces (Halit, de Haan, & Johnson, 2003). However, the specificity of the P400 to face processing has been questioned, and instead it has been suggested to reflect object processing in general (Dawson et al., 2002). Dawson et al. (2002) demonstrated that the amplitude of the P400 in 3- to 4-year-old children differentiated between familiar and unfamiliar objects, where unfamiliar objects elicited a larger amplitude than familiar objects.

Late slow waves. Following the Nc and the P400 a late slow wave can often be observed, with either negative or positive polarity depending on topography. Specifically, a late positive slow wave (PSW) over frontal regions has been related to memory encoding or updating. Once again, this component is not specific to visual object processing, but is relevant to general cognitive mechanisms involved in learning and is therefore relevant to the study of object recognition. A continuously increasing positivity has been interpreted as continued processing/encoding, while a return to baseline is associated with familiar or well encoded stimuli (Bauer, 2006; Bauer et al., 2003). Thus, modulations of the PSW during encoding of novel objects may provide an indication of successful encoding and recognition.

Methods

Description of Experimental Procedure

The three studies in this dissertation were based on different aspects of the same longitudinal ERP experiment carried out on a sample of children at 20 months and 24 months. Therefore, the experimental procedure will be described in this section, while the specific results and conclusions for each study are described in the section that summarizes the studies. First, I will provide a brief overview of the objectives of the three studies.

Brief overview of the research objectives

- To test children's ability to map real familiar words to versions of their referents displaying reduced visual information (overall shape or isolated parts), and if this ability correlates with vocabulary size (Study I).
- To test if children's performance on a behavioral object recognition task predicts the N400 incongruity effect to the same type of stimuli in the ERP experiment (Study I).
- To investigate individual differences in novel word-object mapping, developmental changes, and the relation between ERP measures of successful word learning and vocabulary size (Study II).
- To investigate individual differences in the modulation of the N400 component during learning (as word-object associations are building up), and possible relations with vocabulary size (Study II).
- To explore the relation between visual object processing and successful fast mapping (Study III).

Participants

The age group in focus for the research questions was children between 1 ½ and 2 years of age. This is the time period when vocabulary growth really takes off for most children. Therefore, individual differences are large and productive vocabulary sizes range from only a few words to several hundred words (Eriksson & Berglund, 2002). Because of this it was an ideal age group to study in order to capture differences in neural responses associated with highly different productive vocabulary skills; either newly-emerging vocabularies or fairly rich vocabularies. In order to facilitate comparison to the earlier studies using the same experimental paradigm, we chose the specific ages of 20 months (the same age group as Torkildsen et al., 2008; 2009) and 24 months. The longitudinal design was applied because there were no previous longitudinal studies of neural measures of fast-mapping. Since we know that vocabulary grows so fast around these ages, we reasoned that measuring fast-mapping processes in the same children at different time points could provide very valuable information.

At 20 months, the sample of participants consisted of 77 children (36 boys) that were tested at 20 months +/- 3 weeks. The 24 months sample consisted of 54 children (tested at 24 months +/- 3 weeks). Four of the participants at 24 months had not participated at 20 months (were added in order to boost sample size), and only a subsample of the participants contributed reliable ERP data at both time points (see the individual studies for exact sample sizes for different analyses). Therefore, both cross-sectional and longitudinal analyses were performed. Participants were required to be typically developing children from mono-lingual Swedish speaking families. They were recruited primarily through an invitation sent out by mail to all children in a certain geographical area close to the lab, within the appropriate age range. Contact information was acquired through the official records of birth dates and home addresses in Sweden ('SPAR-registret'). Participants were also recruited through e-mails sent to university employees, through advertisements on campus, as well as an information campaign at local child health care centers.

ERP experiment

Materials

The 20 and 24 months experiments contained different stimulus sets. The auditory stimulus material consisted of 51 common count nouns, 30 used at each time point (15 artifact labels and 15 animal labels) and 60 pseudowords which were phonotactically legal in Swedish (30 at each time point). Thus, there was a slight overlap of nine real words between the two time points, but these words were paired with different picture referents. The auditory material was recorded in an anechoic

chamber by a female voice, speaking in an infant-directed manner, and presented through speakers placed in front of the participants. The visual stimuli consisted of cartoon images of the objects corresponding to the chosen nouns, and fantasy objects and creatures to be paired with the pseudowords, selected from the web-based collection www.clipart.com. Two modified versions of the pictures were created, one displaying only a few isolated parts, and one displaying a black, filled silhouette of the object (see figure 5). EEG was recorded with infant versions of the 128 channel Hydrocel Geodesic Sensor Nets (Electrical Geodesics, Inc.) connected to a Net Amps 300, with a sampling rate of 250 samples/second, referenced to the vertex.

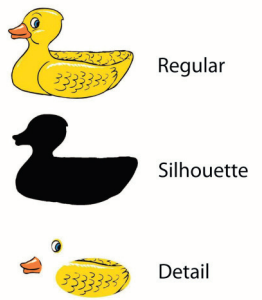

Figure 5. Visual stimulus conditions

Experimental procedure

Children sat on their parent's lap, with a screen placed around them in order to block out distractions. Pictures were presented on a 17 inch computer screen (34 x 27 cm) approximately 35 cm from the child, and words were presented from a speaker next to the screen. Breaks were taken between blocks if necessary, with the possibility of showing a short video clip to recapture the child's attention. A camera placed in front of the child recording the child's behavior throughout the experiment, allowing for exclusion of trials where the child was inattentive. The stimuli were organized into 10 independent blocks, with each block containing 3 real words and objects and 3 pseudowords and novel objects. Each picture-word pair was presented five times in a pseudo-randomized order (see figure 6 for an illustration of the design).

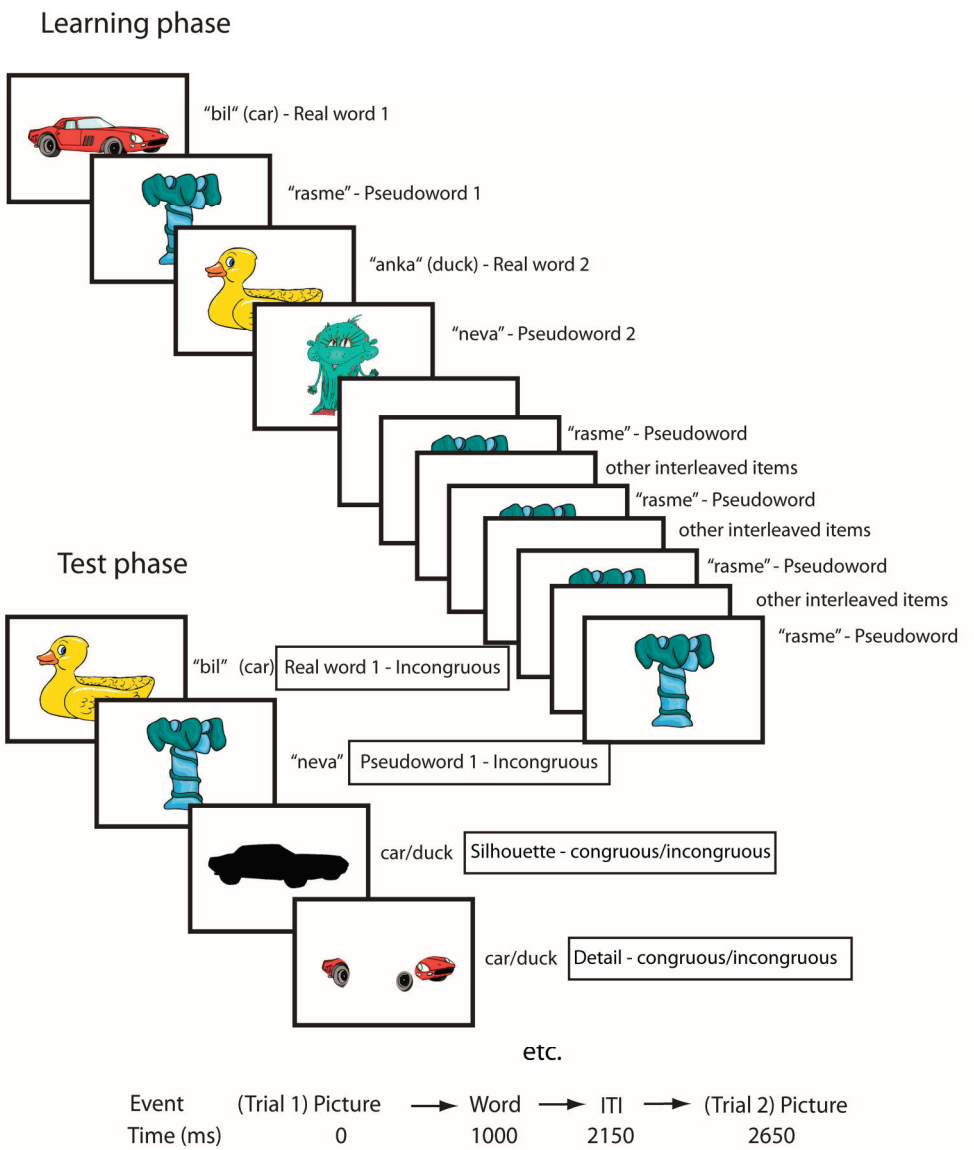

Figure 6. Illustration of the experimental design

The first trial in each block was always a real word, there was at least one interleaved item in between item repetitions, and at most two successive real word trials or pseudoword trials. Each block ended with a test phase, where the picture word pairings were switched. Each word/pseudoword was now presented together with one of the other pictures from the same block, yielding an incongruous pairing. Real objects were always paired with other real words, and novel objects with other pseudowords. Within each block, all words and pseudowords began with different syllables, so that each auditory stimulus could be differentiated from the other words or pseudowords at word onset. In addition to the incongruous pairings, the test phase also included conditions where the modified versions of the original pictures were presented with congruous and incongruous words (modified versions of both real and novel objects were presented). Thus, the test phase contained 10 conditions: regular real objects incongruous, regular novel objects incongruous, real object shapes congruous/incongruous, novel object shapes congruous/incongruous, real object parts congruous/incongruous, and novel object parts congruous/incongruous. Participants were presented with one of two different trial lists, containing the same stimuli but in different pairings (for the pseudowords and novel objects) and presentation order. Pictures were presented for 2150 ms, with a word onset of 1000 ms after each picture onset, and an inter-trial interval of 500 ms showing a white screen.

Analysis

EEG data was pre-processed in the same way in all three studies. The first step was viewing the video time-locked to the data in order to reject sections of the EEG where the child was inattentive. Criteria for being "inattentive" were: not looking at the screen, yawning/looking very sleepy, crying/screaming. A bandpass finite impulse response filter of 0.3-30 Hz was applied, and 1250 ms epochs time-locked to word onset were created, with a 100 ms pre-stimulus baseline. We used an automatic artifact detection procedure in Net Station 4.5 (Electrical Geodesics Inc.) to mark large artifacts and bad channels (max-min voltage changes 200 μV), and trials with more than 15 bad channels were rejected. All trials were then inspected visually and the artifact identification was adjusted so that artifacts caused by eye blinks and eye movements were left in the data for later correction. Remaining bad channels were replaced using spherical spline interpolation. Data was re-referenced to the average of all electrodes (excluding vertical and horizontal eye electrodes and the nasion electrode). An average reference has been argued to be the best reference choice for high-density recordings since it does not bias the signal relative to a specific reference location (e.g. DeBoer, Scott, & Nelson, 2006; Picton et al., 2000). Next, an independent components analysis (ICA) was performed in EEGLAB (Delorme & Makeig, 2004) in order to identify and remove ocular artifacts, and remaining EEG processing was performed in ERPLAB (Lopez-Calderon & Luck, 2014). Only data

from subjects who retained at least ten artifact-free trials per condition were included in the grand average and the statistical analyses.

The specifics of the statistical analyses differed in the three studies, depending on the hypotheses being tested. The fundamental approach, however, was the same. Electrodes were grouped into twelve regions of interest (ROI), covering left, midline and right areas of frontal, central, parietal and occipital regions (see figure 7). Each region contained six electrodes, and the signals from these were averaged into one measure for each ROI. Studies I and II which were only concerned with auditory ERPs (time-locked to the word presentation) did not include occipital regions in the analyses, while Study III which examined visual ERPs covered all twelve regions. The mean amplitude within each time window of interest was used as a measure in all statistical tests. Repeated measures analyses of variance (ANOVAs) were performed to test the experimental effects. Omnibus ANOVAs including all ROIs and conditions were performed first, for each time window separately, followed by more specific analyses for different conditions and regions.

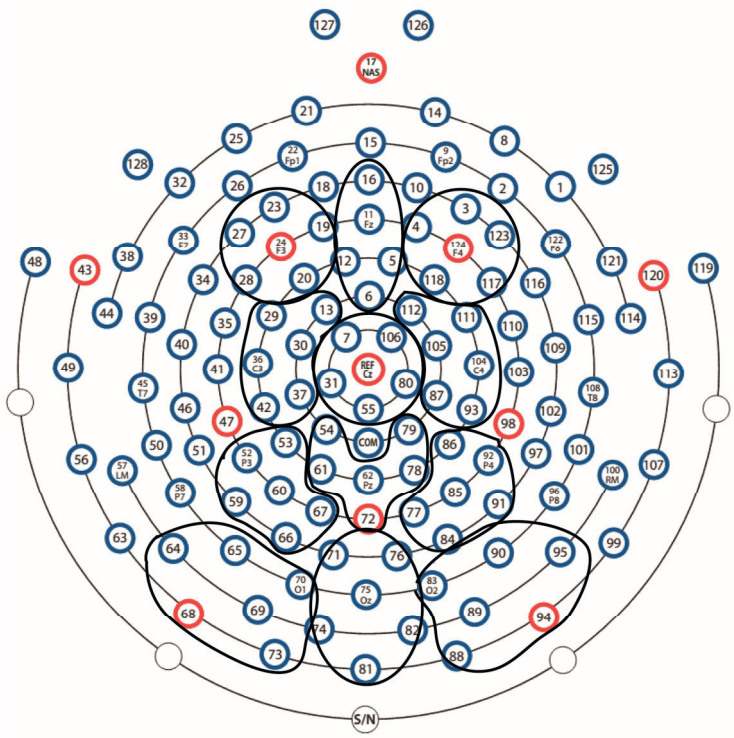

Figure 7. Channel layout of the HCGSN 128, electrodes included in ROIs are circled (Image courtesy of Electrical Geodesics, Inc.).

Behavioral measures

At both time points, parent questionnaires were administered in order to assess the children's language skills and general level of development. These were sent to the parents who were asked to fill them out before their visit to the lab. To assess language skills, a Swedish adaptation of MacArthur-Bates Communicative Development Inventories (CDI Advisory Board, 2006) - the SECDI (Eriksson & Berglund, 2002) was used, in the "Words and Sentences" version. Parents also completed the 20 and 24 months versions of a Swedish adaptation of the Norwegian Ages and Stages Questionnaires (ASQ) (Janson & Smith, 2003; Squires, Potter, & Bricker, 1999). The ASQ assesses the infant's level of development in various areas including language and motor development. This measure was included in order to obtain background information about other areas of development than language.

A behavioral experiment was also performed, for the purposes of the object recognition questions in Study I. The purpose of the experiment was to obtain an overt, explicit measure of children's ability to recognize objects from overall shape information or isolated parts. Participants were asked to point to a picture of an object, among 2 distractors, that corresponded to a given label. Thus, the response measured was pointing to a picture, and this response could be either correct or incorrect, with a 33 % chance level. The stimuli consisted of cartoon images of common objects and animals, and these images were modified in the same way as the ERP stimuli to contain only outline shape information (a black silhouette of the object) or only a few salient details. The images were presented 3 by 3 on a cardboard paper (only stimuli from the same condition were presented on the same paper), and the child was asked: "Where is the car?", or "Can you point to the car?" (or other target word). Objects that were not identified were later presented in their original, full version in order to determine whether the incorrect response was due to the child not knowing the label or not being able to recognize the modified version of the object.

The ERP Technique and its Use in Young Children

The event-related potential (ERP) technique is a method of structuring and analyzing data acquired from the electroencephalogram (EEG). The EEG is a technique for non-invasively recording the brain's ongoing electrical activity by placing electrodes on the scalp. The signal recorded at the scalp is generally the result of postsynaptic potentials occurring in large groups of neurons in the cortex that have a similar orientation and receive the same type of input (Luck, 2005). By acquiring a continuous signal of these activities across the entire scalp, while at the same time

presenting the participant with a specific task or specific stimulus, it is possible to analyze the specific pattern of response associated with a given type of stimulus or cognitive process. This is done by averaging a large number of sections of the EEG that are time-locked to the event of interest. The ERP technique can be used either as an instrument to understand more about specific cognitive processes in different contexts or populations, or in order to gain more knowledge about the neural underpinnings of cognitive processes.

Advantages

A major advantage of the ERP technique is its excellent temporal resolution, with most research setups using a sampling rate of between 250 and 2000 Hz (measuring points between 0.5-4 ms). This enables a fine-grained monitoring of continuous brain activity as stimuli are being processed or specific tasks are being performed. This is a considerable advantage over behavioral measures in the sense that it provides measures of online perceptual and cognitive processes rather than a behavioral response that often is the end result of a cascade of processes that have already taken place and that have distinct stages. When it comes to investigating cognitive processes in infants and young children, this advantage becomes even more apparent. For the most part, it is not even possible to obtain overt behavioral responses in these populations because they will not follow instructions and may not be capable of producing a motor response. Compared to other brain imaging techniques, such as functional magnetic resonance imaging (fMRI) or magnetoencephalography (MEG), EEG is relatively inexpensive and easy to apply to young children. These properties have led to large increase in recent years in developmental studies using EEG to investigate anything from basic, automatic perceptual processes to complex cognitive processes such as memory and language (Csibra et al., 2008; Hoehl & Wahl, 2012).

ERP data can be incredibly rich and reveal subtle developmental changes that occur with age, or individual differences in specific stages of a cognitive process. Due to the precise timing of ERP measures they can often provide more detailed information than other passive response behavioral measures such as looking time or sucking behavior, but ERP measures are particularly useful in combination with different behavioral measures. ERP measures and behavioral measures can often provide complementary information.

Limitations

A disadvantage of EEG measures compared to some other brain-imaging measures (fMRI, near-infrared spectroscopy (NIRS), MEG) is its relatively poor spatial resolution. It is difficult to tell from a given scalp topography of a response where the

response has been generated, and often an ERP component can be the result of related processes in several different brain regions (see Kutas & Federmeier, 2011 for a discussion on multiple sources of the N400). With mathematical models it is possible to estimate a source of an ERP response, but these models are more difficult to build for developing brains and therefore source localization techniques are rarely applied to infant data.

Another difficulty with designing experiments for ERP recording is the need for many trials of the events of interest in order to obtain a reasonable signal-to-noise ratio. This is a more serious limitation for infant/child studies than for adult studies since many trials requires longer experiments, which increases attrition due to the participants' limited attention span. Thus, it is necessary to achieve a balance between reasonable demands on the participants and reasonably good data quality, and that can be difficult to determine beforehand. Because of this, infant studies usually report much fewer trials per condition than what is normally recommended for obtaining good data. The minimum number of trials required per condition differs depending on the size of the component of interest as well as the amount of noise in the data, but while a general recommendation for adult data is around 50 artifact-free trials, infant studies often manage with only 10-20 trials (Hoehl & Wahl, 2012; Luck, 2005). One of the few advantages with recording ERPs in infants compared to adults is the relative ease of obtaining low impedances (the resistance between the electrodes and the scalp) and a larger amplitude of the components, due to factors such as little hair, thin skin and a thinner skull. These aspects may contribute to the possibility of obtaining reasonable data from a relatively small number of trials.

Furthermore, there are several practical difficulties with recording ERPs in infants and young children. Applying the electrodes is rarely popular, and for some participants the experiment session ends abruptly already at this preparatory stage due to intense protests. For those participants who tolerate the electrodes the sensation of wearing them for a long time often leads to unwelcome interference such as little hands grabbing at the electrodes, which leads to displacement and requires adjustment. In the studies presented in this dissertation we used the high-density EEG recording system from Electrical Geodesics Inc. (EGI) which has the advantage of allowing a large number of electrodes to be applied quickly and painlessly (no abrasion of the skin is required), but still some children did not appreciate the sensation of a wet electrode net being pulled onto their head. Compared to behavioral measures, these discomforts may make it more difficult to recruit participants, and often leads to a need for large sample sizes in order to compensate for attrition. Attrition is further increased due to the difficulty of keeping children interested and focused on the task, as well as minimizing movement and blinking which otherwise creates artifacts in the data. There is also a risk that the remaining sample of participants that provide adequate data represents a certain subsample of the population, one that is especially cooperative, tolerant and docile.

Behavioral Measures

Parent ratings

The studies in this dissertation primarily used parent questionnaires as behavioral measures. In order to assess language skills, the Swedish Early Communicative Development Inventories (SECDI) was administered, in the version designed for the targeted age group: "Words & Sentences" (16-28 months) (Eriksson & Berglund, 2002). This instrument is a Swedish adaptation of the MacArthur Communicative Development Inventories (CDI) which was developed in the USA (Fenson et al., 1993). This questionnaire contains a list of 710 words commonly understood and produced by young children, and parents are asked to report which words their child is able to say. This was the measure of the child's productive vocabulary used in the present studies. The questionnaire also covers a few other aspects of language use, such as the length of sentences produced and certain aspects of grammatical competence, but this information was not used in the current studies. The instrument offers population norms for Swedish children that were used to assess the performance of the samples included in the present studies. The reliability and content validity of the SECDI have been examined by Berglund and Eriksson (2000) who found a test-retest reliability for the Words & Sentences (W & S) questionnaire of around 0.90. The content validity was measured in various ways, one was to use a section of the form where parents were asked to give examples of sentences produced by their child and to measure how many of the words reported freely in this section were included in the vocabulary checklist. This analysis showed that from a sample of 900 participants, 91.2 % of words reported six or more times were included in the W & S checklist. This indicates that the checklist covers a substantial proportion of words used frequently in the targeted age group. A study on the predictive validity of a New Zealand version of the CDI showed that the W & S productive vocabulary measures had good predictive validity for vocabulary across a 21 month period. Vocabulary size measured with the CDI at 1;7 correlated significantly with vocabulary measured by the Peabody Picture Vocabulary Test-III at age 3;4 ($r = 0.45$, $p < 0.01$) (Reese & Read, 2000). A recent doctoral dissertation explored the predictive validity of the SECDI and reported a correlation of $r = .68$ ($p < .05$) between productive vocabulary at 18 and 24 months (Eriksson, 2014). Specifically, largest stability between 18 and 24 months was seen in children who scored in the highest quartile, while those in the lower quartiles at 20 months tended to be relatively evenly distributed between all four quartiles at 24 months.

In order to obtain measures of the participants' developmental level in other domains, we also administered a Swedish adaptation of the Norwegian Ages & Stages Questionnaires (ASQ) for 20 and 24 months, which is an instrument developed for

screening purposes and therefore has population norms and cut-off scores for at-risk performance (Janson & Smith, 2003; Squires, Potter, & Bricker, 1999). Swedish norms are not currently available for the ASQ, which is why we used the Norwegian norms. This questionnaire covers the following domains: Communication, Gross Motor skills, Fine Motor skills, Problem Solving, and Personal/Social skills, and each domain contains 6 descriptions of behavior that the parent is asked to determine if their child performs, with the alternatives "Yes", "Sometimes" or "No". The data from the ASQ was used to investigate correlations between ERP-measures and other developmental domains than vocabulary, and as background information. If any participant had scored below the cut-off criterion on several domains of the ASQ, they would have been excluded due to the risk of not belonging to a typically developing population.

Overt responses

The only study in this dissertation that measured overt responses was Study I, which included a behavioral experiment where the participants were asked to point to a picture of an object that corresponded to a given label. A major benefit of an overt response such as pointing is that interpreting the meaning of the response is generally intuitive and straightforward. In this case, it is perfectly clear that a child pointing consistently correct is able to explicitly and consciously both understand the word and recognize its referent. We can conclude that the child's knowledge of the word and its referent is fully functional and can be used in a communicative situation. The biggest disadvantage of relying on such a response, however, is that it is a rather "noisy" measure. In addition to measuring the child's knowledge of the word and recognition of the object, we are also measuring the child's ability and willingness to comply with instructions, to interact with the experimenter, and endurance to complete the task. Therefore, there is a risk of underestimating children's abilities and skewing the sample to consist of a special part of the intended population that is socially compliant and well-behaved. Our experience with the experiment in Study I confirmed that many children were unable or unwilling to complete the task for reasons that probably did not have anything to do with their ability to identify the word referents. Thus, although interpreting a positive overt response is generally straightforward, it is much more difficult to interpret the meaning of a missing or incorrect response.

Stimulus Selection and Considerations

For both the ERP experiment and the behavioral experiment in Study I, we needed to select specific word and picture stimuli. The real words were selected from the SECDI Words & Sentences questionnaire (with a few exceptions) with the following criteria:

- count nouns (objects and animals, 50 % from each category)
- common and likely to be familiar to most children (according to our parent ratings, the participants comprehended on average 21 of the words in the ERP experiment at 20 months, and 26 words at 24 months)
- that their referent could be illustrated to have a distinct outline shape and salient surface details
- contained one to four syllables (most had one or two syllables, but we aimed for variability so that the different words would be easily discriminated). Only one word had 4 syllables ("motorcycle").

The pseudowords were selected/created so that they contained one to three syllables (most of them had two syllables) and that they did not have any obvious similarity to real words likely to be familiar to children in the target age group. For the ERP experiment, all words were recorded in an anechoic chamber by a female voice that spoke in an infant-directed manner (slowly and animated) in order to maximize the infants' attention. The picture stimuli were selected from the picture database on the website www.clipart.com. The pictures were chosen to be colorful, attractive two-dimensional drawings of the real words' referents, and fantasy creatures and strange objects were chosen to be paired with the pseudowords. It was important that the pictures could be modified to reveal only a distinct outline shape/silhouette or a few salient surface details.

There were a few considerations when deciding on the type of visual stimuli to be used. First, we decided to use illustrations rather than realistic photographs of real objects. We wished to closely follow the procedure applied in Torkildsen et al. (2009; 2008) where the same type of illustrations from Clipart were used. There was also an ambition to present stimuli that were similar to the type of toy models of objects used in a number of shape caricature recognition studies (e.g. Pereira & Smith, 2009; Smith, 2003). Although the stimuli in these studies were three-dimensional actual objects that could be manipulated rather than two-dimensional illustrations, they were not realistic exemplars. Since we needed to use two-dimensional stimuli that could be presented on a computer screen, and all previous studies on the shape bias and shape recognition have used three-dimensional objects, we needed to make decisions about how to manipulate the pictures in order to display only overall shape or only parts information. For the shape condition, a silhouette showing only the

outline shape was the most intuitive solution to systematically modify the pictures. Moreover, object recognition research on adults has shown that adults easily recognize objects from outline images, and that such outlines function as primes for object labels (Hayward, 1998; Rosch et al., 1976). Hayward (1998) argues that "outline shape might be particularly crucial for achieving object constancy or recognition across a change in observed viewpoint". This suggests that outline shape may be an important feature for generalization and categorization in a similar way as abstract shape caricatures. It has also been demonstrated that toddlers (and adults) prefer an upright planar viewpoint when handling and viewing three-dimensional objects, which indicates that using two-dimensional planar illustrations of objects is appropriate when studying toddlers' object recognition (Pereira, James, Jones, & Smith, 2010). However, it is still important to keep in mind that two-dimensional outline shape stimuli have not previously been used in any studies concerning the shape bias or shape recognition in children, which means that our results and experimental manipulations cannot be considered equivalent to those in previous research.

It was more difficult to decide on how to manipulate the pictures to reveal only object parts or surface details. In the only previous study comparing object recognition based on abstract shape versus object parts, three-dimensional toy models of objects were created by combining major object parts in either the correct configuration or the incorrect configuration (Pereira & Smith, 2009). Therefore, we considered creating scrambled pictures of the objects which would be somewhat equivalent as all details in the picture would be present only in the wrong configuration and therefore lacking overall shape. However, we were concerned this type of pictures would appear strange and be very difficult for the children to recognize, and therefore we instead decided not to change the configuration of object parts but select and display only a few salient surface details of the object. This meant that the stimuli in the object parts condition displayed a few isolated parts revealing between 30-40% of the original picture. An advantage of this approach was that we considered this a more direct test of the theoretical claim that children progress from object recognition based on "fragments" to that based on overall shape (Smith, 2009), since a fragment is typically understood as "a small part broken off or detached" (American Heritage Dictionary, 2004). Once again though, the difference between our stimuli and those used in previous studies must be kept in mind when interpreting our results.

Research Studies

Study I: Object Shape and its Role in Online Word-Object Mapping and Vocabulary Development (Borgström, Torkildsen, & Lindgren, 2015a)

The focus for study I was inspired by research on the shape bias and shape recognition and the role of object shape in early vocabulary growth (e.g. Pereira & Smith, 2009; Smith, 2003; Smith et al., 2002). This research has led to a theory about the interaction between object recognition abilities and vocabulary development that posits that object recognition progresses from based on individual object features, or "fragments", to overall shape, and that this development is partly driven by vocabulary growth (Smith, 2009, 2013). An improvement in shape recognition is also thought to facilitate further word learning due to increased attention to a dimension that is particularly relevant for object categorization. This development takes place toward the end of the second year of life, and typically as vocabularies reach a size of 50-100 words. All previous studies on this phenomenon have used explicit behavioral measures of object recognition, and when study I was planned, only one study had directly tested children's ability to recognize objects from individual parts compared to overall shape (Pereira & Smith, 2009).

In study I, we sought to expand current evidence for the link between shape recognition and vocabulary by providing electrophysiological measures of the ability to map a word to an object based on object shape information. We also wished to compare these processes to the ability to map a word to an object from fragments, individual parts. Using the longitudinal design, we investigated whether the relation between these object recognition abilities and vocabulary was the same at 20 months, when some children would be at a very early stage of vocabulary acquisition, as at 24 months, when most children would have reached a more advanced level of word learning. The critical measure of these abilities was the N400 incongruity effect to words paired with either shape or parts versions of an object (a larger negative amplitude to incongruous pairs than congruous pairs). A significant N400 incongruity effect would indicate that children were able to recognize the object and link it to its correct label. A correlation between this incongruity effect and vocabulary

size would indicate that children's ability to make this word-object connection was associated with their vocabulary skills.

Analyses were focused on the real word conditions, in order to minimize demands of novel word learning. The N400 incongruity effect to words paired with regular (unmodified) pictures of objects was used as a control condition. This effect was calculated by comparing the incongruous presentation in the test phase with the 5th (final) congruous presentation in the learning phase. For the shape and parts conditions both congruous and incongruous presentations appeared in the test phase of each block, in a randomized order. A behavioral experiment was performed, containing the same type of modified pictures of real objects as the ERP experiment, and performance on this experiment was compared with the ERP results.

The key results were that although the N400 incongruity effect to words paired with regular pictures was present at both ages and was unrelated to vocabulary size, the N400 effect to words paired with object shape correlated with vocabulary. Children with larger vocabularies tended to have a stronger N400 effect (larger amplitude difference) in the shape condition. This pattern was found at both 20 and 24 months, but at 24 months there was no direct correlation with individual vocabulary scores, only an effect of vocabulary group (high or low), which suggests that the relation between shape processing and vocabulary size is stronger and more direct at an early stage of vocabulary development. Behavioral performance on the object identification task also correlated with the N400 effect in the shape condition. In the object parts condition, however, there was no N400 incongruity effect, regardless of vocabulary size or age. Thus, the children did not link the picture of object parts to the correct label, either because they were completely unable to recognize the object, or because the picture activated words associated with the specific parts or features (e.g. wheel, eye etc.) rather than the whole object label.

In sum, the results provide novel evidence that words presented with pure shape versions of their referents are processed differently in the brain in toddlers with small or large vocabularies. We did not, however, find evidence for the progression from object recognition based on parts to that based on shape. Finally, an important note is that although the paper based on study I (Borgström, Torkildsen, & Lindgren, 2015a) only reports results from the real word conditions, the experiment also contained modified versions of the novel objects that had been consistently paired with pseudowords. These conditions were also analyzed, but did not result in any N400 effects at either age. This indicates that the shape of newly familiarized objects, without the additional presence of surface details, is not a sufficient cue for newly learned object labels. Rather, sensitivity to object shape likely increases as objects become highly familiar.

Study II: Effects of Age and Vocabulary on Novel Word Learning Processes (Borgström, Torkildsen, & Lindgren, 2015b)

This study investigated changes in children's ability to map novel words to novel objects during the dynamic period of vocabulary growth between 20 and 24 months. We also examined the relation between vocabulary size and word learning ability, as well as changes in semantic processing during learning. The research questions were inspired primarily by the studies by Torkildsen and colleagues (2009; 2008) showing that 20-month-olds' fast mapping ability was related to vocabulary size, and that the vocabulary groups also differed in modulation of ERP responses during learning. By examining the same age group, and testing the same sample four months later, it would be possible to determine whether these differences related to vocabulary size diminish as vocabulary growth has started to take off for those children who have barely begun to talk at 20 months.

The main focus of analyses was on the pseudoword conditions, and on ERPs time-locked to the presentation of the pseudoword, although responses to real words were analyzed as a comparison. The N400 incongruity effect to the pseudowords (the incongruous pairing in the test phase was compared to the 5th and final congruous pairing in the learning phase) was used as a measure of successful fast mapping of the novel pseudowords to the novel objects. The dynamics of ERP responses to words and pseudowords were investigated by analyzing effects of repetition on two components involved in word processing, the N200-500 and the N400. Participants were divided into two vocabulary groups, according to a median split, which was entered as a between-subject variable in all analyses. Effects of vocabulary size were also analyzed by calculating difference scores for ERP measures and correlating these with the continuous vocabulary variable. Effects of age were investigated in the subsample that contributed data at both time points (n = 23).

In contrast to the results in Torkildsen et al. (2008), the 20-month sample in this study did not produce a significant N400 incongruity effect to newly learned pseudowords at 20 months, regardless of vocabulary size. Four months later, however, there was an effect at the group level which was also unrelated to vocabulary size. Thus, at 24 months the sample as a whole was capable of fully learning the association between novel words and novel objects, although they were unable to do so four months earlier. The dynamics of N400 responses during learning was, however, related to vocabulary size at both ages. Children with large vocabularies showed a linear reduction of N400 amplitude to the pseudowords across the five consistent presentations, while children with smaller vocabularies did not demonstrate this attenuation until the end of the learning phase. The N200-500 component,

which is associated with word familiarity rather than semantic processing, increased in amplitude due to repetition, but these changes were unrelated to vocabulary size. The results indicate that a substantial improvement in rapid word learning ability takes place between 20 and 24 months, a period of time when the participants' actual vocabularies on average tripled in size. Furthermore, the quicker attenuation of the N400 during learning in children with larger vocabulary size indicates that vocabulary size is related to the efficiency of establishing novel word-object associations.

Study III: Visual Object Processing and Fast Mapping Ability in 20-Month-Olds (Borgström, Torkildsen, & Lindgren, submitted)

This study explored the relation between ERP measures of visual object encoding and successful mapping of novel words to those objects. Although fast mapping involves encoding both a novel word form and a novel object, the contribution of visual object processing skills to successful word learning is unclear. Some research has suggested that the rate of habituation of looking time to novel objects in infancy, as a measure of visual attention, predicts future language and other cognitive skills (Colombo et al., 2004; Tamis-LeMonda & Bornstein, 1989).

In contrast to the two previous studies in this dissertation, analyses in this study focused on visual ERP responses time-locked to the picture presentation. The main ERP component of interest was the Nc component, a response associated with attention and that differentiates between novel and familiar events (e.g. Bauer, 2006; Courchesne, 1978). We expected the amplitude of the Nc response to novel objects to decrease as the objects were repeated, indicating an increasing level of familiarity. We hypothesized that the rate of Nc attenuation could be indicative of learning efficiency and therefore would be related to the ability to fast map pseudowords to the novel objects. Fast mapping ability was defined in terms of the strength of the N400 incongruity effect to pseudowords paired with the novel objects. Since the experiment also presented real familiar objects and words, we analyzed the difference in Nc amplitude between the first presentations of novel and real objects, as a measure of recognition of the real objects. We further hypothesized that this measure would predict the strength of the N400 incongruity effect to real words, as a stronger representation of the object may facilitate a stronger association to the object label. Two other visual ERP components were also analyzed and expected to be modulated by novel object repetition, and possibly related to fast mapping ability: the P400 (Dawson et al., 2002; de Haan, 2006), an occipital component related to face and object processing, and a positive slow wave (PSW) that has been related to memory encoding and updating (Bauer, 2006; Bauer et al., 2003). Only the 20-month sample was analyzed for this study, since results from study II indicated that there was potentially a larger variability in fast mapping ability at this age. There was no significant N400 effect to pseudowords at the group level, but we hypothesized that the above measures of object processing might be able to identify a subset of participants that did show evidence of fast mapping.

The results showed that children with a stronger Nc repetition effect during the first three presentations of the novel objects also tended to display a larger difference in the N400 in response to incongruous pseudowords compared to the final congruous

presentation. In fact, a subset of participants (n = 11) with the strongest Nc repetition effect produced a statistically significant N400 incongruity effect, indicating that they had successfully mapped the pseudowords to the correct novel objects. The late slow wave following the Nc component also correlated with the N400 effect in the pseudoword/novel object condition. Neither of these repetition effects for real objects, however, were related to the N400 effect to real words. However, the object recognition effect (Nc difference between novel and real objects) did predict the strength of the N400 effect to real words, suggesting that children with better initial representations of the real objects tended to have better lexical access to the correct label.

Discussion

Summary of Principal Findings

Although not the most spectacular finding, a very important result for all the studies was the fact that all samples produced a significant N400 incongruity effect to real words. This was a critical control condition in order to validate the experiment and establish that the data fulfilled reasonable quality criteria. Although this effect was certainly expected, and many previous studies have shown that infants and young children respond to words in incongruous semantic contexts with a larger N400 component, it is not a trivial result to obtain. Considering the difficulty of engaging toddlers in any structured experiment, and as in the present studies requiring them to concentrate on a computerized stimulus presentation for up to 30 minutes, it was not unthinkable that the collected data might not yield any significant ERP effects at all. Fortunately, this was not the case.

The presence of a clear N400 effect at both ages and in all the samples used in the different studies shows that the participants were reasonably engaged in the task and processed the relation between the words and the objects presented. In other words, they performed the task as it was intended. Interestingly, the N400 incongruity effect to real words was unrelated to vocabulary size in our studies. Previous research has reported mixed results, with some studies showing that infants with larger vocabularies are more likely to produce an N400 effect than those with smaller vocabularies (Friedrich & Friederici, 2004, 2006, 2010; Rämä et al., 2013), while other studies report no such relation (Torkildsen et al., 2008). Most likely, the mixed results depend on differences in experimental design, where some studies have a familiarization/learning phase, which has the potential to decrease initial differences between children in word knowledge, while others only present congruous and incongruous trials in a randomized fashion. Moreover, at younger ages it is more likely that children with different productive vocabulary sizes also have different receptive knowledge of the specific word stimuli used, or that all children are relatively unfamiliar with the specific words and that the task therefore brings out differences in novel word learning. The present studies involved older infants, and incorporated a familiarization phase in order to decrease difference in prior familiarity with the specific word stimuli. Therefore it is not surprising that there was no relation

between the N400 effect and vocabulary size. However, the pseudoword condition also involved a familiarization phase, and despite this the 20 month sample did not produce an N400 effect in this condition. This indicates that the N400 effect to real words was, at least in part, dependent on pre-existing representations of the words and/or the objects involved which had a scaffolding effect on the learning during the familiarization phase. When all stimuli were completely new, the familiarization phase was not enough for the 20-month-olds as a group to fully establish associations between the pseudowords and the objects.

This brings us to the second main finding in this dissertation, which concerns the N400 incongruity effect to pseudowords. The N400 incongruity effect was used as a critical measure of whether participants had learned the novel associations between the pseudowords and the fantasy objects. Although the 20-month-olds as a group did not show such an effect, the same children at 24 months did show a significant effect. This leads us to believe that the children had made "substantial gains in word learning ability between 20 and 24 months" (as stated in the title of Study II). During a period of rapid vocabulary growth (on average a three-fold increase in vocabulary size) the children demonstrated a clear change in ERP responses to incongruous word-object pairings. Under the same experimental conditions, they were suddenly able to learn the referential relation between novel pseudowords and novel objects which they failed to learn only 4 months earlier. We had expected this word learning ability, as manifested by the N400 incongruity effect, to correlate with vocabulary size as reported in Torkildsen et al. (2008) in 20-month-olds. However, this was not the case at either age in the present sample, which we believe was due to the specific demands of the present experiment, which were higher than in the former study. Whereas not even high producers were able to learn the novel words at 20 months under these experimental conditions, most children succeeded at the task at 24 months, and thus vocabulary size did not differentiate between ERP responses.

Another major finding also concerned the N400 component, and its modulation during learning rather than its response to semantic incongruity (also reported in Study II). Toddlers with large productive vocabularies showed the same attenuation across multiple repetitions as is commonly seen in older children and in adults (De Bruin, Martens, Glimmerveen, & Van Strien, 2008; Deacon et al., 2004; Doyle et al., 1996; Petten et al., 1991; Van Strien, Glimmerveen, Martens, & De Bruin, 2009), while low producers required several presentations before the N400 amplitude started to decrease. This repetition effect on the N400 has not previously been demonstrated in infants. The results suggest differences in encoding efficiency of the word-object associations, where high producers already after one learning episode start to be semantically primed by the picture. These differences were only found for completely novel word-object stimuli, while for real objects and words low producers showed the same linear attenuation of the N400 due to repetition. So, for words and objects that the children already had some representation of, one pairing was enough

for even low producers to create a semantic expectation from the picture. Previous studies on infants and word learning have primarily reported repetition effects on the earlier appearing N200-500 component, which is interpreted as a word familiarity effect. This component increases in amplitude as words become more familiar. Several studies have reported an association between N200-500 effects and vocabulary size, where infants with larger vocabularies show either larger word familiarity effects or repetition effects after fewer presentations. In our samples we did not find any association between this component and vocabulary size, instead vocabulary was relevant for the modulation of the N400 component. This is probably because the associations between the N200-500 and vocabulary have primarily been reported in samples of younger infants (Junge & Cutler, 2014; Junge, Kooijman, et al., 2012). In the older age groups included in the present studies, it is reasonable that the more mature N400 component is more sensitive to differences in language skills.

Although we found no differences between children with large or small vocabularies in terms of their ability to learn the novel pseudoword-object associations (the N400 incongruity effect), we did find that a subsample of the 20 month-olds were better learners than the rest, and actually produced a significant N400 incongruity effect. This group was defined by their relatively quick habituation of visual ERP responses to the novel objects, which is reported in Study III. This result suggests that toddlers who more quickly and efficiently encode visual information about novel objects are better at associating a novel word to this object. Such a link between neural measures of visual object processing and semantic processing of words has not been reported previously. It appears to be an interesting parallel to findings showing that a classical measure of visual habituation in young infants (decrease in looking time) in response to repeated presentations of visual stimuli correlates with future language and cognitive skills (Colombo et al., 2004; Tamis-LeMonda & Bornstein, 1989). Quicker habituation has generally been interpreted as an indication of more efficient encoding (Colombo & Mitchell, 2009; Colombo et al., 2010), an interpretation which may be applied to the attenuation of ERP amplitude of several visual ERP components (the Nc, P400 and late slow waves) observed in Study III. Interestingly, this relation between the visual repetition effect and the N400 was specific to the novel word-object condition. For real words and objects, on the other hand, an ERP measure of initial object recognition (the difference in Nc amplitude between real and novel objects on their first presentations) predicted the size of the N400 incongruity effect. In other words, quick habituation of visual responses were relevant to producing an N400 incongruity effect for completely novel stimuli, while for relatively familiar stimuli, the strength of pre-existing representations of the objects were related to the strength of the N400 effect.

Finally, Study I also reports important findings regarding the relation between object processing and word processing. We found that at 20 months a larger vocabulary was associated with a larger N400 incongruity effect to real familiar words presented in

incongruous shape contexts. This N400 effect at 20 months also predicted vocabulary at 24 months. This correlation was specific to the shape condition showing object silhouettes, since the N400 effect in regular picture contexts was unrelated to vocabulary size. Several studies have shown that object recognition based on shape is related to vocabulary size around the time of the vocabulary spurt (Gershkoff-Stowe & Smith, 2004; Jones & Smith, 2005; Pereira & Smith, 2009; Smith, 2003; Smith et al., 2002), but these have all used behavioral measures. No previous studies have demonstrated or investigated the link between shape recognition and word learning using neural measures. Also, by using a different type of stimuli in Study I than in previous shape recognition studies (2D silhouettes rather than 3D shape caricatures) we were able to show that the relevance of shape recognition for vocabulary development extends to outline shape.

Limitations

This section will discuss limitations of the studies with regards to the research methodology. The next section about implications will take into account further limitations with regards to the broader conclusions that can be drawn from the results.

Experimental design

Due to the ambition of obtaining longitudinal data, and the large number of participants required in order to retain reasonable sample sizes after attrition, a single experiment was designed to incorporate many different research questions. The benefit of this approach was efficiency of data collection, but it also had certain drawbacks. The experiment became long and demanding, and it is possible that we may have obtained different results if we instead had divided the experiment into two less demanding experiments. One experiment could have focused on the questions regarding object recognition based on shape or individual parts, and used only real familiar stimuli and modified versions of the pictures. Another experiment could have focused on novel word learning and thus contained fewer conditions. Lowering demands in this way may have resulted in lower attrition rates and perhaps better learning, especially at 20 months.

In the present experiment the incongruous words (in the regular picture condition) were compared to the 5th congruous presentation for the N400 incongruity effect, but a limitation of this is that the 5th presentation is always presented before the incongruous presentation, i.e. the order of presentation is not random. If I had been

able to design the experiment over again, I would have added a congruous regular picture condition in the "test phase", so that instead of comparing incongruous word-picture pairings to the 5th congruous presentation, there would be a 6th congruous presentation that was presented in random order among the incongruous presentations. This was the case in the shape and detail conditions in Study I. However, I do not believe this limitation in the design affected the results, because if anything one would expect that the order would decrease the N400 amplitude in the later presented condition (the incongruous condition) due to repetition attenuation, but since we consistently found a significant incongruity effect in the real word condition (i.e. larger amplitude to incongruous presentations), this effect is unlikely to be caused by order of presentation. Possibly, such an order effect could have contributed to the lack of an N400 incongruity effect to pseudowords in 20-month-olds. However, the study by Torkildsen et al. (2008) where 20-month-olds with large vocabularies did produce such an effect, had the same methodological weakness.

The stimuli used in Study I to test recognition based on shape or detail differed quite substantially from stimuli used in previous studies. Although this enabled us to extend current knowledge concerning shape recognition, it also complicated direct comparison with other studies. In particular, the results from our behavioral experiment differed from previous results showing a positive correlation between shape recognition and vocabulary already at 20 months, while in our results this correlation appeared at 24 months. And, more importantly, our completely novel way of displaying object parts did not yield the results expected based on previous research. Most likely, the detached object parts were not viewed as objects that could function as a prime for the whole-object word. Therefore this condition probably did not engage the same process seen previously where children with smaller vocabularies were better able to recognize objects from parts information (Pereira & Smith, 2009).

Interpretation of data

Although our interpretations of the ERP components rest on a history of extensive research regarding the components of interest, it is still a limitation of ERP research that the functional significance of a certain ERP component is less intuitive and straightforward than many behavioral measures, such as asking a child to point to a labelled object. What does the presence of an N400 incongruity effect really tell us about the child's knowledge of a word? Would the child be able to use that knowledge explicitly to for instance behaviorally identify the referent of the word? Although we know that the 24-month-old participants learned some relation between the novel objects and pseudowords, since they produced a significant N400 effect at the group level, it is difficult to know what sort of knowledge of these words they actually possessed at the end of the experiment, or even at the end of each experimental block.

With regards to analyzing the EEG data, we chose to follow standard procedures of the event-related potential technique, and similar analyses as previous research studies in the field. However, EEG data is extremely rich, and alternative ways of analyzing the data may have contributed valuable information. For instance, source localization techniques may have added to our understanding of the different components involved in our experimental tasks, and also may have highlighted differences between groups of participants. Although there are studies that have used source localization on infant data, the field still lacks appropriate pediatric head models that are reliable enough (Song et al., 2013). Such models are underway and should greatly facilitate source localization analyses on infant data in the future.

Finally, a central ambition of this dissertation was to obtain the first longitudinal data set using this type of fast mapping ERP task. However, the sample of participants included in analyses at both time points (n = 23-24) was considerably lower than the cross-sectional samples (n = 33-38), and we reasoned that the extra data provided by the full sample at each time point was too valuable to exclude. Thus, analyses were primarily based on the two age groups separately, although longitudinal analyses on the smaller subsample were performed to investigate effects of age specifically. It is possible that the longitudinal sample in some way differs systematically from the specific age samples which could be a limitation to our conclusions, although there are no such indications. For instance, measures of vocabulary size in the longitudinal sample do not differ considerably from the rest.

Implications

The purpose of this dissertation was to investigate individual differences in infants' ability to learn word-object associations, as manifested both by parent ratings of productive vocabulary and measures of online processing and learning. We were especially interested in the relation between these two measures. So, after summarizing the main results of the studies, have we learned anything new about this subject? And if so, what implications does this new knowledge have on our understanding of the development of children's word learning skills?

First of all, the large individual differences in productive vocabulary size typically observed were found in the tested sample as well. There was a similar spread of vocabulary skills as in the reference population, which indicates that the sample was reasonably representative of the population in terms of vocabulary development. However, as is discussed in paper 2, we noted that our participants had a slightly faster vocabulary growth rate than the CDI reference group (scored around the median at 20 months, but in the 65th percentile at 24 months). This may be due to the relatively high SES among the participating families.

Associations between productive vocabulary and the N400

As expected we found that the individual differences in productive vocabulary size were associated with different ERP responses during processing of word-object references, which are processes of comprehension. Specifically, a larger vocabulary was associated with a stronger N400 incongruity effect to real words in a shape context, as well as a quicker attenuation of the N400 component during learning of novel pseudoword-object pairs. These results suggest that children with larger vocabularies are better at processing the semantic relation between a word and the overall shape representation of its referent, which is in line with results from behavioral studies showing that children with larger vocabularies are better at identifying objects based on shape information (Pereira & Smith, 2009; Smith, 2003). Our results also suggest that children with larger vocabularies more quickly reach a certain ease of semantic processing of novel word-referent associations. However, we did not find that this, in a sense more efficient semantic learning, was critical for fully learning the word-object association within the framework of the experiment. Instead, at 20 months it was not enough to establish the association, and at 24 months, it was not essential, and even the "slower" learners managed to learn the association. This implies that, although differences in vocabulary skills are reflected in the modulation of the N400 component, we cannot tell directly from a specific pattern of N400 modulation whether a child will be able to learn a novel word-object association or not.

An interesting question concerning the nature of the relation of the N400 component and vocabulary is whether the differences in N400 responses are due to differences in pre-existing knowledge of the specific words being processed, or whether they apply to semantic processing in general. It is inevitable that specific word knowledge influences the N400 response, since word comprehension is essential for an incongruity effect to occur, or semantic priming to attenuate the N400 amplitude. However, the present studies also demonstrated that vocabulary size is related to differences in N400 modulation to completely novel words, that none of the children had previous experience with. This indicates that the brain mechanisms that give rise to the N400 component differ in general between children with small or large vocabularies.

Furthermore, the link we observe between vocabulary size and N400 responses is correlational, and we therefore cannot draw any clear conclusions about the nature of the relationship and whether there is a causal link. Assuming that lower N400 amplitude is a manifestation of less effortful semantic processing, we still do not know whether children have larger vocabularies because of more efficient mechanisms of semantic processing in the brain, or whether a large vocabulary and the experience of verbal communication improve these brain mechanisms. It is possible that in some children, these mechanisms develop to be more efficient at an earlier age, due to general brain maturation, which in turn enables them to easily learn new words and

build a large vocabulary. Alternatively, there may be no systematic differences in brain maturity between children with differing vocabulary skills. Instead, other factors in the environment or in the child's personality may influence the development of a larger vocabulary, which may in itself alter the mechanisms of semantic processing in the brain. The appendix of this dissertation reports additional analyses of the correlations between vocabulary and N400 effects while controlling for nonverbal level of development. This control is important and shows that there is a link between these variables that are independent of children's general, nonverbal, level of development.

The link between object processing and word processing

The results in both Study I and Study III demonstrate a link between word processing and visual object processing. The results indicate that children who more quickly encode a novel object are more likely to be able to map a novel word to that object, and that better recognition of a familiar object is associated with a stronger link to the object's verbal label. Also, children with larger vocabularies more easily access an object's verbal label when only the object shape, and no surface details, is available. These links between object processing and word mapping skills highlight the importance of general memory mechanisms for word learning, and not only language specific word processing skills. In the background section of this dissertation I emphasized that learning word meanings is a matter of forming associative memory representations. From this perspective it follows that better encoding of one item (e.g. the object) can facilitate the encoding of an associative link to a second item (e.g. the word). The findings from Study III support this view of word learning as an associative memory process. Similar results have not been reported previously, so the direct correlations found between our measures of object processing and word mapping are valuable.

Development in word learning from 20 to 24 months

The reason for adopting a longitudinal experimental approach was to capture the dynamics of word learning skills around the time of the vocabulary spurt. We wanted to see whether the relation between vocabulary size and certain semantic processing skills changed depending on a child's stage of vocabulary acquisition (i.e. very early in vocabulary acquisition – below 75-100 words, or later – above 100 words). With regards to this question, our results are mixed. The correlation between vocabulary size and sensitivity to object shape was only present at 20 months, when there was a wide range of vocabulary sizes in the sample. This suggests that it was primarily children with particularly small vocabularies below 75 words that were less able to use object shape as a semantic cue. This supports the theory held by Linda Smith and

colleagues (Smith, 2009, 2013; Smith et al., 2010) that attention and sensitivity to object shape in labelling contexts is something that develops as children's vocabularies reach a certain size and they are able to see certain patterns in how objects are categorized. On the other hand, the correlation between vocabulary size and N400 modulation during novel word learning was present at both 20 and 24 months, and thus seem not to be specifically tied to certain vocabulary sizes. It remains an open question whether differences in vocabulary size at older ages are associated with different rates of N400 attenuation during learning.

Concerning the experimental test of having learned novel word-object pairings, the N400 effect to pseudowords, the lack of correlation with vocabulary size at either age was surprising. Since neither vocabulary group demonstrated an N400 incongruity effect to the pseudowords at 20 months, we cannot say that children with small vocabularies "caught up" with their peers by 24 months with regards to this word learning skill. Although the whole group, independent of vocabulary size, showed evidence of learning at 24 months, we do not know whether there were ever any differences in this measure between children with small or large vocabularies. It is possible that children with larger vocabularies would have succeeded at the task at an earlier time point between 20 and 24 months, and that those with smaller vocabularies had caught up by the time they returned to the lab at 24 months, but that is purely speculative. However, the fact that there was such a major development in the N400 effect to newly learned words between 20 and 24 months points to what is probably the most striking feature of early word acquisition: that word learning skills improve at a remarkable rate during the second year of life. Although this ERP measure was not directly correlated with vocabulary size in our studies, it is hard to imagine that this development in fast mapping ability would be completely unrelated to the three-fold increase in productive vocabulary observed during the same time period. Thus, the idea that development in fast mapping skills in part account for vocabulary growth during the second year could find support in our data. However, the fact that we did not find direct correlations between these measures also emphasizes the complexity of early vocabulary growth and the factors that influence it. For instance, object encoding efficiency was a better predictor of fast mapping success than vocabulary size, which indicates that certain cognitive skills are relevant to word learning under the specific demands of the experiment, but may be of less important for word learning in real life.

This brings us to an important final reflection concerning the results presented in this dissertation. The word learning situation created in the laboratory is of course widely different from an ordinary word learning situation for an infant in real life. Objects and words were presented rapidly on a computer screen, with no social interaction involved. Also, no response was expected from the child who may have been more or less involved in the task. Objects were labelled ostensibly with a single word, thus there was no need to extract a word from continuous speech and no element of

ambiguous mapping. This design has both advantages and drawbacks, the advantages being that we were able to isolate the most basic elements of word learning which are encoding a single word and its referent and establishing an associative memory trace of the two items. The observed association between parent-reported vocabulary and brain responses measured in this restricted context suggests that our task tapped processes relevant for real life learning. However, in real life the many other factors that influence vocabulary growth, such as language input and social cognitive skills, come into play and may reduce the impact of the cognitive skills reflected in our ERP measures.

Future Directions

An important aspect of word acquisition, which was not at all examined in the studies in this dissertation, is the process of generalizing from variable input. In a natural environment children must learn from experience with several different exemplars of objects and then extend their word knowledge to novel exemplars. This could be implemented experimentally in a design similar to Junge et al.'s (2012) which employed real categories of objects. In order to genuinely study the novel word learning situation similar sets of artificial stimuli could be created that formed word categories. It would be interesting to compare learning from single exemplars and multiple exemplars and see if children differ in these abilities at certain ages, and whether individual differences are related to differences in vocabulary size. Research using behavioral measures has shown that experience with more dissimilar, variable category exemplars can lead to better abstraction of object categories in toddlers (Perry, Samuelson, Malloy, & Schiffer, 2010), but these factors have not been investigated in an ERP paradigm. Using ERP measures, 9-month-olds have been shown to be able to learn word meanings from several exemplars using immediate tests of learning (Junge, Cutler, et al., 2012), and 9- to 16-month-olds have been shown to benefit from sleep in order to be able to generalize word meanings after a delay (Friedrich et al., 2015). Yet we know little about how these abilities develop and about possible individual differences and their relation to vocabulary size. The distinction between forming precise memories for individual items and generalizing to new instances was recently highlighted in a review of sleep-dependent learning effects across early childhood (Gómez & Edgin, 2015). It seems that the age period of 18-24 months marks a transition from better generalization after sleep to better precis memory after sleep. These findings should be taken into account in future studies comparing the learning of specific word-object association with word generalization to novel exemplars of a category.

One of the limitations of the experimental paradigm used in this dissertation is the unclear nature of the knowledge the children have obtained when producing an N400 incongruity effect. Due to the limited attention span of the tested age group additional behavioral tests, or comprehension tests using other methods, were not possible to add to the present studies. However, in future studies that focus solely on novel word learning it might be possible to add explicit behavioral comprehension tests after each experimental block (e.g. asking the child to point to a labelled object among a number of distracters). An alternative could be to add eye-tracking measures to see if the child looks reliably longer at the correct labelled object compared to a distracter. In addition, tests of retention could be added, although the number of novel words taught most likely needs to be reduced substantially (from the 30 items taught in the present paradigm) in order to see evidence of retention at these ages.

Regarding the relation between vocabulary and object recognition based on shape or individual features, there is still very little research concerning the role of parts-based recognition and whether this indeed is something that precedes shape-based recognition. Future studies should continue to investigate what specifically characterizes the parts-based object recognition, comparing the effects of different types of stimuli. One should also attempt to more directly test the changes in shape processing as vocabularies grow from before to after the point of the vocabulary spurt. Study I attempted to do this with its longitudinal design, but the timing of the two experiments was still determined at a group level, at 20 and 24 months. Ideally, one would recruit and test children who are all at a clearly pre-vocabulary spurt stage, monitor individual children's vocabulary growth and re-test them at the very point where word learning accelerates, as well as after their vocabularies are well established at a post-vocabulary spurt level. This would capture the dynamics of vocabulary growth and the neural processes related to the mapping of words to different visual properties of objects.

Furthermore, we have hypothesized that Nc attenuation due to repetition can be conceived of as a form of habituation of visual attention. It would be desirable to better test the causal link between such visual repetition responses and word learning, by trying to actually manipulate novel object encoding to measure the effect on word learning. This could for instance be done by trying to influence attention to the object, through social interaction (joint attention), variability in input, longer presentation time etc.

Finally, a crucial issue to investigate more closely is how word learning through fast mapping (based on cortical mechanisms) relates to word production vs. word comprehension. Studies of fast mapping, those reported in this dissertation included, tend to only test learning in terms of word comprehension. For instance, the study by Sharon et al. (2011) involving amnesic adults included no test requiring recall of the learned word, only a word comprehension/matching task. Similarly, studies of fast

mapping in children generally test learning using looking behavior, explicit pointing/fetching of an object, or ERPs, neither of which requires actual recall. Although the present studies show several correlations between such comprehension measures and productive vocabulary, there is a knowledge gap where we do not really know how these comprehension skills are transferred to expressive knowledge.

Future research could begin with healthy adults and compare results on comprehension and production tasks after incidental or explicit learning. Similar tasks could be designed for children (although they probably need to be at least 3 to 4 years old), where novel word-object associations were taught either through ostensive labelling or in an ambiguous mapping task (or the same type of incidental learning task used in Sharon et al. (2011)). The knowledge acquired could then be tested in different ways: by actual recall/labelling of an object, explicit forced-choice recognition, as well as passive measures such as the N400. Ideally, one would also include a delay overnight followed by a re-test to test the effect of consolidation.

Appendix

This appendix presents the results from additional analyses that are relevant to the general conclusions of the research project, but did not fall within the scope of the three articles. In addition, a full list of all word stimuli used in the ERP and behavioral experiments can found at the end of the appendix.

Effects of Word Type During the Learning Phase

First of all, several analyses were performed on the longitudinal sample (n = 23) to compare the processing of real words vs. pseudowords in general during the learning phase (i.e. only when the word and object stimuli were consistently paired). The purpose was to explore how word form processing and semantic processing differed between the two word types, and whether there were any effects of age or vocabulary size.

Word form processing

The effect of word type (real word or pseudoword) on the N200-500 component was first tested including all word stimuli (presentation 1-5) at both time points (20 and 24 months). The measure used was the mean amplitude between 200 and 400 ms at frontal channels. This analysis showed a main effect of word type on the N200-500 component, with no interaction with age, $F(1,22) = 8.61$, $p = .008$, $\eta_p^2 = .281$. The N200-500 amplitude was more negative in response to real words than to pseudowords, indicating that the real words were perceived as more familiar. However, when the analysis included only the first presentation of the stimuli, there was no significant effect of word type, suggesting that the phonological form of the pseudowords was processed similarly to the real words before the stimuli were repeated.

Semantic processing

The same analyses as those described above were performed to test the effect of word type on the N400 component (mean amplitude between 400 and 800 ms at parietal channels). When all word and pseudoword trials were included, there was a main effect of word type on the N400 amplitude, where pseudowords elicited a larger negative amplitude than real words, $F(1,22) = 21.31$, $p < .001$, $\eta_p^2 = .492$. This effect was significant even when only the first presentation of the stimuli were analyzed, $F(1,22) = 13.11$, $p = .002$, $\eta_p^2 = .373$. This suggests that the children understood the meaning of the real words already the first time they were presented, and that the meaning of the real words continued to be more easily accessed throughout the learning phase, even though some learning of the pseudowords took place.

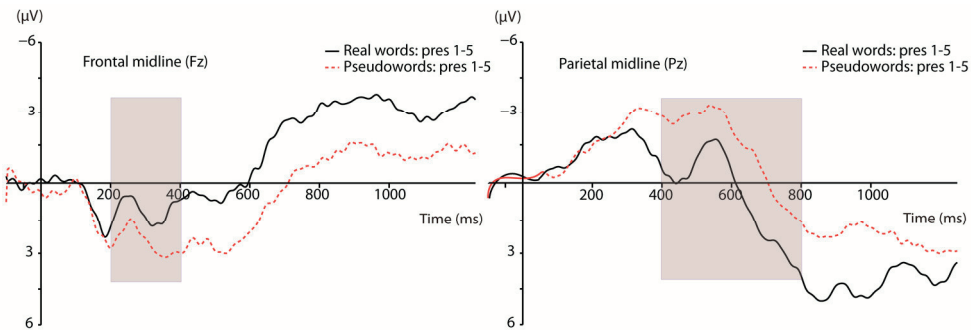

Figure 8. Grand average ERP waveforms of all real words vs. all pseudowords in the learning phase (24 months longitudinal sample, n = 23). Frontal midline channel displayed on the left, with N200-500 time window highlighted, and parietal midline channel displayed on the right, with N400 time window highlighted.

Effects of vocabulary size

In order to investigate whether the processing differences between real words and pseudowords were associated with the children's vocabulary size, the difference amplitude for each component was correlated with vocabulary size at 20 months (n = 38) and 24 months (n = 33) separately. The processing of the first presentations of each word type was of particular interest, since the effects of repetition were investigated in study II.

The N400 difference score between the first presentation of words and pseudowords was significantly correlated with productive vocabulary at 20 months, $r = -.367$, $p = .023$. Children with larger vocabularies tended to have a larger difference (relatively

more negative amplitude to pseudowords than real words). At 24 months, the same correlation was not significant, $r = -.329$, $p = .062$.

In contrast, the N200-500 difference score (for the first presentation) did not correlate with vocabulary size at either age, 20 months: $r = .127$, $p = .449$; 24 months: $r = .034$, $p = .852$.

These results indicate that children with larger vocabularies more easily processed the meaning of the real words the first time these were presented, compared to their peers with smaller vocabularies (particularly at 20 months). The specific auditory word form, however, was equally novel for real words and pseudowords on first presentation (they had never heard this particular token of the word stimulus before), which led to similar phonological processing as reflected in the earlier frontal component.

The idea that children with larger vocabularies had better semantic representations of the real words already at the start of the experiment is supported by the fact that, at 20 months, there was a significant difference between the vocabulary groups in the number of real words in the experiment that parents rated as comprehended. The mean number of experimental words comprehended in the HV group was 25 (out of 30) compared to 17 in the LV group, $t = -4.72$, $p < .001$. At 24 months the difference was smaller, yet still significant: 28 words in the HV group and 24 words in the LV group, $t = -2.33$, $p = .028$.

Specificity of ERP – Vocabulary Correlations

Consistent with the purpose of this dissertation, productive vocabulary size was found to correlate with several ERP measures of word and object processing. However, the possibility remains that these correlations exist primarily due to shared correlations with children's general level of development. The studies did not include a standardized IQ test, or administered test of general development, such as the Bayley Scales of Infant and Toddler Development (Bayley, 2006). Instead, in order to minimize the time spent in the lab and the demands placed on the child, the ASQ parent questionnaire was administered. An "ASQ Nonverbal" total score was calculated for each child, including all the scales except the "Communication" scale which contained items related to language comprehension and production.

To check whether the correlations between vocabulary and certain ERP measures were due to children's general level of development, all vocabulary-ERP correlations found to be significant were re-analyzed as partial correlations controlling for the ASQ Nonverbal score.

Table 1. Correlation coefficients for ERP measures related to productive vocabulary, before and after controlling for nonverbal development.

ERP measure	Bivariate correlation with Productive Vocabulary	Partial correlation – controlling for ASQ Nonverbal
N400 shape incongruity effect – 20 mths (Study I)	r = -.425, p = .008	r = -.377, p = .021
N400 repetition effect for pseudowords – 20 mths (Study II)	r = .347, p = .036	r = .353, p = .035
N400 repetition effect for pseudowords – 24 mths (Study II)	r = .394, p = .023	r = .394, p = .026

As can be seen in table 1, all correlations were significant even when controlling for the ASQ Nonverbal score. The only correlation that was affected was that between productive vocabulary and the N400 incongruity effect in a shape context (reported in Study I). In fact, analyses showed that this incongruity effect was significantly correlated with the ASQ Nonverbal score, r = -.457, p = .004 (when controlling for vocabulary size: r = -.415, p = .011). In other words, our measure of semantic processing of words in an object shape context was related to both vocabulary size and the child's level of development in nonverbal domains. In a linear regression model these two variables each contributed significantly to the model, $F(2, 35) = 8.29$, p = .001, R^2 = .321. The coefficients for the two predictors were: Productive vocabulary, β = -.343, $t(35)$ = -2.41, p = .021; ASQ Nonverbal, β = -.383, $t(35)$ = -2.70, p = .011. Thus, these two factors together were found to explain 32.1 % of the variance in the N400 shape incongruity effect. The N400 repetition effects analyzed in study II were completely uncorrelated with the ASQ Nonverbal score.

Study III found no significant correlations between the ERP measures investigated and vocabulary size. However, the visual repetition effect that predicted the N400 incongruity effect to pseudowords could in turn be correlated with nonverbal development. Partial correlations showed that this was not the case, the Nc repetition effect was still strongly correlated with the N400 effect, even when controlling for the ASQ Nonverbal score, r = -.473, p = .004. The ASQ Nonverbal score was completely uncorrelated with either of these two ERP measures.

Word Stimuli – ERP and Behavioral Tasks

Table 2. Word stimuli used in the ERP task. Real words included both at 20 and 24 month displayed in italics.

Pseudoword – 20 m	Real word – 20 m	English translation	Pseudoword – 24 m	Real word – 24 m	English translation
blägge	bil	car	apätt	apa	monkey
dallabell	byxor	pants	bamm	bi	bee
dorisant	ekorre	squirrel	batatin	björn	bear
hode	fisk	fish	båpir	bord	table
kas	fjäril	butterfly	dusk	buss	bus
kong	fluga	fly	elke	motorcykel	bicycle
lafa	flygplan	airplane	fime	flaska	bottle
lömm	fågel	bird	fåpe	giraff	giraffe
minge	groda	frog	fätte	gris	pig
mocki	helikopter	helicopter	gilp	katt	cat
nakit	häst	horse	hönt	klocka	clock
neva	kossa	cow	jyne	kyckling	chicken
olk	lejon	lion	kuff	lamm	lamb
pemm	motorcykel	motorcycle	lebosuf	lampa	lamp
pule	nalle	teddybear	losa	lastbil	truck
rasme	sko	shoe	lubåb	mus	mouse
rilke	sköldpadda	turtle	mira	pingvin	penguin
rime	stol	chair	nuru	telefon	telephone
röbenör	strumpa	sock	pale	tiger	tiger
sallotan	tandborste	toothbrush	pelun	traktor	tractor
saro	tupp	rooster	piba	träd	tree
sibb	*anka*	*duck*	pyka	*anka*	*duck*
smate	*blomma*	*flower*	rup	*blomma*	*flower*
tabar	*båt*	*boat*	ryne	*båt*	*boat*
tare	*elefant*	*elephant*	sulp	*elefant*	*elephant*
tenegor	*hund*	*dog*	sume	*hund*	*dog*
tibbe	*kanin*	*rabbit*	tile	*kanin*	*rabbit*
tjeg	*klänning*	*dress*	tjule	*klänning*	*dress*
vir	*tåg*	*train*	tuke	*tåg*	*train*
votter	*vagn*	*stroller*	vurev	*vagn*	*stroller*

Table 3. Word stimuli used in the behavioral task.

Word stimuli – 20 m	English translation	Word stimuli – 24 m	English translation
bil	car	anka	duck
blomma	flower	bi	bee
cykel	bicycle	blomma	flower
fjäril	butterfly	bord	table
fisk	fish	båt	boat
flygplan	airplane	elefant	elephant
får	sheep	flaska	bottle
gris	pig	giraff	giraffe
groda	frog	kanin	rabbit
hund	dog	klänning	dress
hus	house	kyckling	chicken
katt	cat	tiger	tiger
lampa	lamp	traktor	tractor
mus	mouse	vagn	stroller
sköldpadda	turtle		
träd	tree		
tröja	shirt		
tåg	train		

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