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Procedural learning across the lifespan: A systematic review with implications for atypical development

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This systematic review aimed to investigate procedural learning across the lifespan in typical and atypical development. Procedural learning is essential for the development of everyday skills, including language and communication skills. Although procedural learning efficiency has been extensively studied, there is no consensus yet on potential procedural learning changes during development and ageing. Currently, three conflicting models regarding this trajectory exist: (1) a model of age invariance; (2a) a model with a peak in young adulthood; and (2b) a model with a plateau in childhood followed by a decline. The aims of this study were (1) to investigate this debate on procedural learning across the lifespan by systematically reviewing evidence for each model from studies using the serial reaction time task; and (2) to review procedural learning in autism spectrum disorder (ASD) and specific language impairment (SLI), two developmental disorders characterized by deficits in communication skills, in the light of these models. Our findings on typical development strongly support a model of age-related changes (Model 2a or 2b) and show that mixed findings regarding the developmental trajectory during childhood can be explained by methodological differences across studies. Applying these conclusions to systematic reviews of studies of ASD and SLI makes it clear that there is a strong need for the inclusion of multiple age groups in these clinical studies to model procedural learning in atypical development. Clinical implications of the findings are discussed. Future research should focus on the role of declarative learning in both typical and atypical development.

We are able to acquire a variety of skills during our lives, from riding a bike to communicating our needs, and we are especially good at learning these skills when we are young. Motor skills, social skills, and language are all thought to develop largely through ‘procedural’ learning mechanisms (e.g., Lieberman, 2000). Procedural learning refers to learning that occurs unintentionally and (relatively) outside awareness (Reber, 1967). An

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astonishing example of procedural learning is that of grammar learning in young children, whereby children quickly and unintentionally acquire complex grammar rules they are completely unaware of. During normal development, this process seems to occur naturally and without much effort. However, if an adult tries to learn a second language intentionally, a fair amount of effort is involved and conscious awareness of the learned grammar rules is required, often making language learning a struggle. This type of intentional, effortful learning is often referred to as 'declarative learning'.

Empirical evidence (arguably) supports a distinction between procedural and declarative learning, not only at a functional level (e.g., Destrebecqz & Cleeremans, 2001; Haider & Frensch, 2005) but also at a neurobiological level (e.g., Fletcher *et al.*, 2005; Squire, 2004). Declarative learning relies mainly on the medial-temporal lobe (MTL) memory system, including the hippocampus and surrounding cortical areas, with critical connections to other areas of the brain such as the prefrontal cortex (as reviewed by Reber, 2013). Procedural learning, on the other hand, is subserved by larger brain networks depending on the nature of experience (Reber, 2013). More specifically, procedural skill learning involves the fine-tuning of perceptual–motor systems, thus including the cerebellum and basal ganglia (Janacsek, Fiser, & Németh, 2012; Krishnan, Watkins, & Bishop, 2016). However, overlap between neural substrates of these learning mechanisms has also been reported, particularly regarding the role of the hippocampus (e.g., Hannula & Greene, 2012), and a minority of authors argue that the procedural and declarative learning can in fact be explained by a unitary learning mechanism (e.g., Berry, Shanks, & Henson, 2008).

The most commonly used paradigm to study procedural learning during typical and atypical development is the serial reaction time (SRT) task (Nissen & Bullemer, 1987). In this task, a participant is asked to respond to stimuli shown at one of four locations on a computer screen by pressing a corresponding button. Unknown to the participant, the stimuli are presented in a repeating sequence. Sequence learning is reflected in a decrease in reaction times (RTs) for sequenced stimuli and an increase in RTs for random stimuli. The procedural nature of the learning is confirmed by the unintentional nature of the learning (i.e., there is no instruction to learn) and the absence of (full) awareness of the sequence. Being relatively easy to administer and analyse, the SRT task is a widely used task in research on procedural learning during typical and atypical development (Abrahamse, Jiménez, Verwey, & Clegg, 2010).

Given that communication skills are thought to develop largely through procedural learning, this type of learning has been studied extensively in autism spectrum disorder (ASD) and specific language impairment (SLI), two neurodevelopmental disorders that are both characterized by deficits in language and social and communication skills (Geurts & Embrechts, 2008; Vissers & Koolen, 2016). Most studies examining procedural learning in ASD and SLI have used the SRT task (Foti, De Crescenzo, Vivanti, Menghini, & Vicari, 2015; Lum, Conti-Ramsden, Morgan, & Ullman, 2014), and procedural learning on the SRT task has indeed been associated with language impairments in SLI (e.g., Ullman & Pierpont, 2005) and with social communication skills in general (Lieberman, 2000). However, findings on procedural learning in ASD and SLI are mixed (for a meta-analysis, see Obeid, Brooks, Powers, Gillespie-Lynch, & Lum, 2016). This might be related to a potential compensatory role of declarative learning suggested in both disorders (e.g., Ullman & Pullman, 2015), which could affect task performance in different ways, depending on task characteristics. An additional potential factor is age-related changes in procedural learning in ASD and SLI, of which little is yet known.

Despite the consensus that procedural learning is crucial for skill development, the changes in procedural learning capacities across the lifespan are less clear. Currently, three dominant models exist that aim to explain this trajectory (see Figure 1 for a schematic representation of these models). The original model proposed by Reber (1993) states that procedural learning is invariant over life; it develops relatively early and remains intact across the remainder of the lifespan. This age invariance is explained by the association of procedural learning with evolutionary old brain regions (such as the basal ganglia and the cerebellum), which mature early in life and are relatively unaffected by neurological impairment (Reber, 1993). Support for this model is found in study findings of adultlike procedural learning abilities in young infants (e.g., Saffran, Aslin, & Newport, 1996) and in studies failing to find significant differences in procedural learning between children and adults (e.g., Meulemans, Van der Linden, & Perruchet, 1998). Given its position that procedural learning does not vary with age, the model thus gives rise to the prediction that children, adolescents, younger adults, and older adults would all show similar procedural learning capacities.

However, in contrast to the Reber (1993) model, two more recently developed models contend that procedural learning does indeed vary as a function of age. The first of these models supposes that procedural learning follows an inverted U-shape trajectory, similar to that observed for declarative learning and other cognitive functions (referred to as 'Model 2a'). According to this model, procedural learning depends on frontostriatal regions that show developmental changes well into adolescence (e.g., Thomas *et al.*, 2004), a claim supported by evidence from studies demonstrating enhanced performance in young adults compared to children and older adults (e.g., Lukács & Kemény, 2015). However, another contrasting model developed by Janacsek *et al.* (2012) considers the period between birth and adolescence as critical to procedural learning (referred to as 'Model 2b'). Model 2b is based on evidence for two distinct, competing learning mechanisms: a 'model-free' learning mechanism that detects raw probabilities and relies on the basal ganglia and a 'model-based' learning mechanism that is based on internal models and relies on the prefrontal cortex and MTL (Daw, Niv, & Dayan, 2005). The model-free learning mechanism is assumed to result in a better utilization of raw probabilities in relatively simple skill learning paradigms such as the SRT task. Engaging this mechanism would therefore lead to better task performance compared to the model-based learning mechanism. Janacsek *et al.* (2012) have suggested that model-free learning

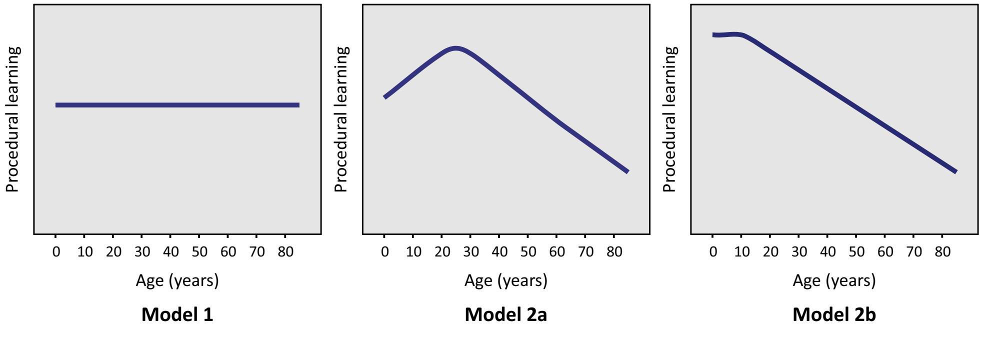

Figure 1. Schematic representation of developmental models of procedural learning, with Model 1 (left) showing an age-invariant development, Model 2a (centre) showing a peak in young adulthood, and Model 2b (right) showing a plateau in childhood followed by a decline from early adolescence.

is predominant in procedural learning before adolescence and model-based learning is predominant from adolescence onwards, with a decline in learning during old age caused by increased rigidity of these internal models. Thus, according to Model 2b, children up until the age of 12 years would perform best, followed by younger adults and then older adults, whereas Model 2a predicts that young adults outperform both children and older adults.

Taken together, there are currently three dominant models explaining procedural learning across the lifespan, each theoretically founded and supported by empirical evidence. However, it is not clear yet which model is most strongly supported as there is as yet, to the best of our knowledge, no full overview of the relevant literature. Establishing how procedural learning changes across the lifespan would not only contribute to understanding typical development (TD), but would also provide a framework to interpret findings in atypical development. This framework would help to explain whether findings of altered procedural learning in atypical development are due to a delay, a deficit, or a different trajectory, yielding different scientific and clinical implications. The aims of this review were (1) to identify which model of procedural learning in TD is the most accurate based on the current literature and (2) to explore how procedural learning in ASD and SLI varies as a function of this model. To achieve this, we systematically reviewed empirical findings of procedural learning across the lifespan from studies using the SRT task in TD, ASD, and SLI, respectively.

Procedure

The search terms and study selection criteria were based on those used for previous meta-analyses on the topic (i.e., Foti *et al.*, 2015; Lum *et al.*, 2014; Obeid *et al.*, 2016). All searches were conducted in PubMed and PsycINFO (Ovid) using keywords for procedural learning and the SRT task (see Appendix). Regarding the searches for TD, additional search terms regarding the developmental aspect were included while studies with a patient population were excluded. For the ASD and SLI searches, additional specific medical subject headings (MeSH) for the disorders were used. Searches had no beginning date and were updated until January 2017. Common inclusion criteria for typical and atypical development included that the paper (1) had an experimental design (i.e., no meta-analysis, review, or case study); (2) studied procedural learning; and (3) used a visuo-motor version of the SRT task (i.e., no auditory SRT tasks were included, to minimize between-study differences). For TD, additional inclusion criteria were as follows: (1) the comparison of multiple age groups; and (2) no clinical populations included. For atypical development, this second inclusion criterion was replaced by the inclusion of the clinical population (i.e., ASD or SLI). The screenings of titles and abstracts were conducted by two authors independently (FSZ and either CThWMV or JHRM). Any disagreements were discussed until consensus was reached. To extend our search, the retrieved papers were screened for additional studies.

Once all studies were selected, the outcome measures of each one were evaluated in terms of effects of interest and dependent variables. These measures were found to be highly heterogeneous: Learning effects were sometimes defined as changes over time, and at other times as a difference between sequenced and random stimuli; some studies focused on performance improvements during the task, whereas other studies were interested in improvements at a later time point; the dependent variable varied between raw RTs, normalized RTs, raw accuracy, and normalized accuracy. To give an overview of the conclusions of each study, the findings are summarized in Tables 1–4 according to the authors' conclusions, with a focus on learning effects as measured during the task.

Typical development

Fifty studies, all focusing on age differences in procedural learning on the SRT task, were included as a result of the systematic database search. Figure 2 summarizes the selection of studies in line with the PRISMA guidelines (Moher, Liberati, Tetzlaff, Altman, & Prisma Group, 2009). Figure 3 gives a graphic illustration of all study conclusions on learning during the task. A minority of these studies (n = 17) support a model of age invariance (see Table 1), with the majority of studies (n = 33) supporting a model of age variance (either Model 2a or Model 2b; see Table 2). We will discuss the empirical evidence from studies on procedural learning during childhood and ageing, and how the methodological differences between studies might have contributed to the different conclusions.

Empirical evidence for the model of age invariance (Model 1)

Evidence for age invariance in procedural learning through childhood comes from five studies (see Table 1), although developmental differences have been reported for accuracy and (baseline) RTs within these studies. One longitudinal study over a 12-month period showed that the procedural learning effect is similar in 5.5- and 6.5-year-olds (Lum, Kidd, Davis, & Conti-Ramsden, 2010). Two studies have reported greater gains in RT measures during initial learning for younger compared to older children (i.e., Karatekin, Marcus, & White, 2007; Mayor-Dubois, Zesiger, Van der Linden, & Roulet-Perez, 2016), which could be interpreted as stronger learning and hence evidence for Model 2b. However, the authors of both studies argued that higher baseline RTs in the younger groups allow for more RT gains, and hence, a difference in baseline speed, rather than in learning, caused the findings. This is not fully agreed upon, with other authors arguing that these baseline differences are part of the developmental trajectory and should therefore not be corrected for (Janacsek *et al.*, 2012). A lower overall accuracy in younger compared to older children has also been reported (Karatekin *et al.*, 2007; Meulemans *et al.*, 1998), with one study showing a proportionally higher error rate for random trials compared to sequenced (learned) trials for the youngest group (Meulemans *et al.*, 1998), suggesting a stronger learning effect. The two other studies did not find accuracy differences between age groups (Mayor-Dubois *et al.*, 2016; Thomas & Nelson, 2001).

The remaining 12 studies support the model of age invariance with findings of relatively spared procedural learning in ageing. In line with the baseline speed problem evident in the studies with children, one study has found that initial greater learning-related gains in raw RTs in older adults disappeared after normalizing the RT data (i.e., Bhakuni & Mutha, 2015). Two studies have reported that although learning is evident later in the task, older adults need more practice to show sequence-specific learning in RT measures compared to young adults (Daselaar, Rombouts, Veltman, Raaijmakers, & Jonker, 2003; Fraser, Li, & Penhune, 2009). Importantly, this was true despite higher baseline RTs in the older adults in both studies, which makes correcting for baseline speed arguable. The findings regarding accuracy are mixed, with one study reporting no age differences (Bhakuni & Mutha, 2015), four studies reporting higher accuracies for younger adults (i.e., Daselaar *et al.*, 2003; Foster & Giovanello, 2017; Fraser *et al.*, 2009; Verneau, van der Kamp, Savelsbergh, & de Looze,

Table 1. Overview of studies on procedural learning using the serial reaction time task in typical development supporting models of age invariance

Studies supporting model of age invariance (n = 17)

Study	Children ages	Adults ages	Model
Bhakuni and Mutha (2015)		*M* (*SD*) = 22.7 (-) years (n = 15) *M* (*SD*) = 63.7 (-)years (n = 15)	I
Bo *et al.* (2012)		*M* (*SD*) = 20.1 (3.2) years (n = 21) *M* (*SD*) = 71.9 (4.5) years (n = 19)	I
Daselaar *et al.* (2003)		*M* (*SD*) = 32.4 (1.8) years (n = 26) *M* (*SD*) = 66.4 (2.0) years (n = 40)	I
Foster and Giovanello (2017)		Experiment 1 *M* (*SD*) = 20.3 (2.1) years (n = 29) *M* (*SD*) = 73.9 (5.7) years (n = 29) Experiment 2 *M* (*SD*) = 18.7 (0.9) years (n = 30) *M* (*SD*) = 66.0 (4.8) years (n = 28)	I
Fraser *et al.* (2009)		*M* (range) = 24 (18–35) years (n = 18) *M* (range) = 65 (60–78) years (n = 15)	I
Frensch and Miner (1994)		Experiment 1, 2 *No focus on age groups* Experiment 3 *M* (*SD*) = 18.8 (1.3) years (n = 55) *M* (*SD*) = 73.7 (7.3) years (n = 54)	I
Gaillard, Destrebecqz, Michiels, and Cleeremans (2009)		*M* (*SD*) = 22.7 (2.7) years (n = 40) *M* (*SD*) = 45.5 (3.4) years (n = 37) *M* (*SD*) = 71.3 (7.0) years (n = 37)	I
Howard and Howard (1989)		*M* (*SD*) = 22.2 (4.9) years (n = 20) *M* (*SD*) = 71.3 (3.1) years (n = 20)	I
Howard and Howard (1992)		Experiment 1 *M* (*SD*) = 19.4 (1.2) years (n = 20) *M* (*SD*) = 73.4 (3.8) years (n = 20)	I, but age differences were found in post-experimental task

Continued

Table 1. (*Continued*)

Studies supporting model of age invariance ($n = 17$)			
Study	**Children ages**	**Adults ages**	**Model**
		Experiment 2 M (SD) = 20.6 (2.4) years (n = 20) M (SD) = 72.3 (3.8) years (n = 20)	
Karatekin *et al.* (2007)	M (SD) = 9.9 (0.5) years (n = 35) M (SD) = 12.7 (1.0) years (n = 28) M (SD) = 15.4 (1.0) years (n = 13)	M (SD) = 20.3 (2.2) years (n = 24)	I
Lum, Kidd, *et al.* (2010)	Longitudinal groups M (SD) = 5.5 (0.4) years (n = 40) M (SD) = 6.5 (0.5) years (n = 40) TD group for retest M (SD) = 6.5 (0.3) years (n = 27)		I, longitudinal study
Mayor-Dubois *et al.* (2016)	M (range) = 8.5 (7.8–8.9) years (n = 24) M (range) = 10.3 (9.8–10.8) years (n = 24) M (range) = 12.5 (11.7–12.9) years (n = 21)		I
Meulemans *et al.* (1998)	M (range) = –(6–7) years (n = 32) M (range) = –(10–11) years (n = 32)	M (range) = –(18–27) years (n = 32)	I
Rieckmann, Fischer, and Bäckman (2010)		M (SD) = 24.7 (3.1) years (n = 14) M (SD) = 68.1 (2.9) years (n = 13)	I, relatively spared
Salthouse, McGuthry, and Hambrick (1999)		M (SD) = 30.3 (5.7) years (n = 67) M (SD) = 49.6 (5.3) years (n = 71) M (SD) = 68.0 (6.2) years (n = 45)	I
Thomas and Nelson (2001)	Experiment 1 M (range) = 7.8 (7.3–7.9) years (n = 22) M (range) = 10.6 (10.2–10.9) years (n = 20)	.	I

Continued

Table 1. (*Continued*)

Studies supporting model of age invariance (n = 17)

Study	Children ages	Adults ages	Model
	Experiment 2 M (range) = 4.8 (4.1–4.9) years (n = 46)		
Verneau *et al.* (2014)		M (SD) = 22.5 (2.7) years (n = 20) M (SD) = 58.6 (3.6) years (n = 18)	I

Table 2. Overview of studies on procedural learning using the serial reaction time task in typical development supporting age variance models

Studies supporting models of age variance ($n = 33$)

Study	Children ages	Adults ages	Model
Bennett *et al.* (2007)		*M* (*SD*) = 20.0 (1.5) years ($n = 12$) *M* (*SD*) = 71.9 (6.0) years ($n = 12$)	2a or 2b
Bennett *et al.* (2011)		*M* (*SD*) = 18.9 (0.7) years ($n = 14$) *M* (*SD*) = 67.6 (3.1) years ($n = 14$)	2a or 2b
Bo and Seidler (2010)		Experiment 1 *M* (*SD*) = 20.7 (1.6) years ($n = 48$) *M* (*SD*) = 73.9 (5.4) years ($n = 48$) Experiment 2 *M* (*SD*) = 22.9 (2.0) years ($n = 12$) *M* (*SD*) = 73.7 (3.8) years ($n = 12$) Experiment 3 *M* (*SD*) = 22.4 (3.8) years ($n = 12$) *M* (*SD*) = 70.9 (3.5) years ($n = 12$)	Task characteristics interact with age
Bo *et al.* (2011)		*M* (*SD*) = 21.4 (2.5) years ($n = 14$) *M* (*SD*) = 72.7 (4.0) years ($n = 14$)	2a or 2b
Brown *et al.* (2009)	-	*M* (*SD*) = 20.4 (1.6) years ($n = 14$) *M* (*SD*) = 58.3 (3.8) years ($n = 12$)	2a or 2b
Cherry and Stadler (1995)		Experiment 1 *M* (*SD*) = 22.9 (5.1) years ($n = 66$) *M* (*SD*) = 67.2 (5.7) years ($n = 22$) *M* (*SD*) = 67.9 (4.5) years ($n = 22$)	2a or 2b

Continued

Table 2. (*Continued*)

Studies supporting models of age variance (n = 33)

Study	Children ages	Adults ages	Model
		Experiment 2 *M* (*SD*) = 21.5 (2.0) years (n = 40) *M* (*SD*) = 68.1 (5.8) years (n = 40) *M* (*SD*) = 69.6 (4.4) years (n = 40)	
Curran (1997)		Experiment 1 *M* (range) = 'undergraduates' (n = 32) *M* (range) = 67.3 (60–79) years (n = 39) Experiment 2 *M* (range) = 'undergraduates' (n = 64)	2a or 2b
De Guise and Lassonde (2001)	*M* (range) = 7.2 (6–8) years (n = 10) *M* (range) = 10.1 (9–11) years (n = 10) *M* (range) = 12.8 (12–14) years (n = 10) *M* (range) = 15.3 (15–16) years (n = 10)		2a for bimanual task
Dennis and Cabeza (2011)		*M* (*SD*) = 22.2 (3.5) years (n = 12) *M* (*SD*) = 67.4 (6.7) years (n = 12)	Different neural substrates between age groups
Ehsani *et al.* (2015)		*M* (*SD*) = 29.2 (3.5) years (n = 30) *M* (*SD*) = 64.8 (4.0) years (n = 30)	2a or 2b
Feeney *et al.* (2002)		*M* (*SD*) = 41.4 (3.0) years (n = 23) *M* (*SD*) = 49.4 (2.5) years (n = 22)	2a or 2b
Fischer *et al.* (2007)	*M* (*SD*) = 9.4 (1.4) years (n = 14)	*M* (*SD*) = 24.3 (3.1) years (n = 12)	2a or 2b

Continued

Table 2. (*Continued*)

Studies supporting models of age variance ($n = 33$)

Study	Children ages	Adults ages	Model
Harrington and Haaland (1992)		M (SD) = 20.9 (3.3) years ($n = 15$) M (SD) = 20.4 (2.7) years ($n = 31$) M (SD) = 76.3 (4.8) years ($n = 15$) M (SD) = 77.2 (5.8) years ($n = 30$)	2a or 2b
Hodel *et al.* (2014)	Experiment 1 M (range) = 4.7 (4.1–5.0) years ($n = 60$) Experiment 2 M (SD) = 4.7 (-) years ($n = 30$)	Experiment 1 M (SD) = 23.1 years ($n = 60$) Experiment 2 No adult comparison group	2a
Howard and Howard (1997)		Experiment 1 M (range) = 20.3 (19–22) years ($n = 6$) M (range) = 71.2 (65–87) years ($n = 6$) Experiment 2 M (range) = 21.0 (20–23) years ($n = 6$) M (range) = 69.0 (65–73) years ($n = 6$) M (range) = 77.7 (76–80) years ($n = 6$) Experiment 3 M (range) = 20.3 (19–22) years ($n = 6$)	2a or 2b
Howard and Howard (2001)		Incidental learning group: M (range) = 21.0 (20–23) years ($n = 6$) M (range) = 73.3 (65–80) years ($n = 12$)	2a or 2b
Howard, Howard, Dennis, *et al.* (2004)		M (SD) = 19.9 (1.6) years ($n = 36$) M (SD) = 71.9 (4.5) years ($n = 36$)	2a or 2b

Continued

Table 2. (*Continued*)

Studies supporting models of age variance (n = 33)

Study	Children ages	Adults ages	Model
Howard Howard, Japikse, *et al.* (2004)		*M* (*SD*) = 19.8 (1.0) years (n = 24) *M* (*SD*) = 71.0 (5.0) years (n = 24)	2a or 2b
Janacsek *et al.* (2012)	*M* (*SD*) = 5.3 (1.0) years (n = 30) *M* (*SD*) = 7.1 (0.6) years (n = 55) *M* (*SD*) = 9.9 (0.6) years (n = 35) *M* (*SD*) = 11.5 (0.5) years (n = 29) *M* (*SD*) = 14.9 (1.1) years (n = 62)	*M* (*SD*) = 23.1 (3.7) years (n = 63) *M* (*SD*) = 35.0 (4.2) years (n = 59) *M* (*SD*) = 50.8 (5.1) years (n = 36) *M* (*SD*) = 69.9 (6.2) years (n = 52)	2b
Lukács and Kemény (2015)	*M* (range) = 7.9 (7–9) years (n = 64) *M* (range) = 9.8 (9–11) years (n = 63) *M* (range) = 11.9 (11–14) years (n = 63) *M* (range) = 15.5 (14–18) years (n = 57)	*M* (range) = 20.6 (18–25) years (n = 37) *M* (range) = 29.4 (25–35) years (n = 37) *M* (range) = 40.8 (35–45) years (n = 28) *M* (range) = 49.8 (45–55) years (n = 45) *M* (range) = 60.0 (55–65) years (n = 43) *M* (range) = 72.1 (65+) years (n = 43)	2a
Meissner *et al.* (2016)		*M* (*SD*) = 23.7 (0.6) years (n = 20) *M* (*SD*) = 36.3 (1.4) years (n = 20) *M* (*SD*) = 60.2 (1.5) years (n = 20)	Different
Nejati *et al.* (2008)		*M* (*SD*) = 23.2 (6.2) years (n = 15) *M* (*SD*) = 64.4 (4.5) years (n = 15)	2a or 2b
Németh and Janacsek (2010)		3 conditions 1. *M* (*SD*) = 20.8 (1.1) years (n = 23) 2. *M* (*SD*) = 21.7 (4.2) years (n = 31) 3. *M* (*SD*) = 19.9 (1.3) years (n = 17) 1. *M* (*SD*) = 66.4 (6.2) years (n = 23)	2a or 2b

Continued

Table 2. (*Continued*)

Studies supporting models of age variance ($n = 33$)

Study	Children ages	Adults ages	Model
		2. M (SD) = 67.4 (5.3) years ($n = 22$) 3. M (SD) = 65.2 (4.1) years ($n = 13$)	
Németh *et al.* (2013)	M (SD) = 11.6 (0.7) years ($n = 24$) M (SD) = 14.7 (0.5) years ($n = 21$) M (SD) = 17.0 (0.4) years ($n = 24$)	M (SD) = 21.7 (3.0) years ($n = 45$) M (SD) = 34.8 (2.2) years ($n = 27$)	2b
Németh, Janacsek, Londe, *et al.* (2010)		M (SD) = 21.0 (1.2) years ($n = 11$) M (SD) = 69.8 (7.3) years ($n = 13$)	2a or 2b
Savion-Lemieux *et al.* (2009)	M (range) = 6.4 (6.0–6.8) years ($n = 13$) M (range) = 8.6 (8.3–8.7) years ($n = 12$) M (range) = 10.3 (10.2–10.8) years ($n = 13$)	M (range) = 24.4 (20–34) years ($n = 15$)	2a
Shin (2011)	M (SD) = 9.3 (2.0) years ($n = 26$)	M (SD) = 20.4 (1.2) years ($n = 26$)	2a
Schuck *et al.* (2013)		M (range) = 25.1 (20–30) years ($n = 80$) M (range) = 65.8 (60–71) years ($n = 70$)	2a or 2b
Spencer *et al.* (2007)		M (SD) = 20.8 (2.1) years ($n = 38$) M (SD) = 59.0 (11.1) years ($n = 32$)	2a or 2b
Thomas *et al.* (2004)	M (range) = 9.6 (7–11) years ($n = 9$)	M (range) = 27.9 (23–33) years ($n = 10$)	2a

Continued

Table 2. (*Continued*)

Studies supporting models of age variance ($n = 33$)			
Study	Children ages	Adults ages	Model
Vandenbossche *et al.* (2014)		*M* (range) = 19.8 (18–25) years ($n = 45$; divided over 3 conditions) *M* (range) = 65.4 (55–75) years ($n = 45$; divided over 3 conditions)	2a or 2b
Verwey *et al.* (2011)		*M* (range) = 22 (18–28) years ($n = 24$) *M* (range) = 58 (55–62) years ($n = 24$)	2a or 2b
Weiermann and Meier (2012)	*M* (*SD*) = 11.6 (4.1) years ($n = 50$)	*M* (*SD*) = 23.2 (2.3) years ($n = 50$) *M* (*SD*) = 72.9 (2.3) years ($n = 50$)	2a or 2b

Table 3. Overview of studies on procedural learning using the SRT task in ASD and whether the findings suggest a procedural learning deficit

Study	Group ASD ages	TD ages	Procedural learning deficit?
Barnes *et al.* (2008)	M (SD) = 11.6 (1.7) years (n = 14)	M (SD) = 11.0 (1.8) years (n = 14)	No
Brown *et al.* (2010)	M (SD) = 11.6 (1.1) years (n = 31)	M (SD) = 11.7 (1.5) years (n = 31)	No
Gordon and Stark (2007)	M (range) = 10.9 (6–14) years (n = 7)	M (range) = 12.3 (9–14) (n = 9)	Yes
Izadi-Najafabadi *et al.* (2015)	M (SD) = 8.6 (1.4) years (n = 15) M (SD) = 8.7 (1.4) years (n = 15)	M (SD) = 8.7 (1.6) years (n = 16) M (SD) = 9.2 (1.6) years (n = 16)	No
Mostofsky *et al.* (2000)	M (range) = 13.3 (6.8–17.8) years (n = 11)	M (range) = 12.5 (8.3–16.7) years (n = 17)	Yes
Müller *et al.* (2004)	M (SD) = 28.4 (8.9) years (n = 8)	M (SD) = 28.1 (8.3) years (n = 8)	No
Németh, Janacsek, Balogh, *et al.* (2010)	M (SD) = 11.8 (3.1)[3] years (n = 13)	M (SD): 11.6 (3.3) years (n = 14)	No
Sharer *et al.* (2015)	M (SD) = 10.5 (1.4) years (n = 17)	M (SD) = 10.6 (1.3) years (n = 36)	No, but neural correlates seem to differ
Sharer *et al.* (2016)	M (SD) = 38.7 (18.4) years (n = 18)	M (SD) = 36.4 (17.4) years (n = 11)	Yes, subtle group differences; no overall learning differences
Travers *et al.* (2015)	M (SD) = 20.8 (4.0) years (n = 15)	M (SD) = 21.4 (2.9) years (n = 15)	Yes
Travers *et al.* (2010)	M (SD) = 19.0 (2.9) years (n = 15)	M (SD) = 19.0 (2.1) years (n = 18)	No

Note. ASD = autism spectrum disorder; SRT = serial reaction time; TD = typical development.

Table 4. Overview of studies on procedural learning using the SRT task in SLI and whether the findings suggest a procedural learning deficit

Study	Group SLI ages	TD ages	Procedural learning deficit?
Clark and Lum (2017)	*M* (*SD*) = 9.8 (1.7) years (*n* = 25)	*M* (*SD*) = 9.7 (1.4) years (*n* = 27)	Yes
Conti-Ramsden, Ullman, and Lum (2015)	*M* (*SD*) = 9.8 (0.8) years (*n* = 45)	*M* (*SD*) = 9.8 (0.7) years (*n* = 46)	Yes
Desmottes, Maillart, et al., 2016	*M* (*SD*) = 10.2 (1.6) years (*n* = 18)	*M* (*SD*) = 10.1 (1.7) years (*n* = 17)	Yes
Desmottes *et al.* (2016b)	*M* (*SD*) = 10.2 (1.5) years (*n* = 21)	*M* (*SD*) = 10.5 (1.8) years (*n* = 21)	Yes
Gabriel *et al.* (2011)	*M* (*SD*) = 10.2 years (1.5) (*n* = 16)	*M* (*SD*) = 10.2 (1.5) years (*n* = 16)	No
Gabriel *et al.* (2013)	*M* (*SD*) = 9.6 (1.6) years (*n* = 23)	*M* (*SD*) = 9.6 (1.5) years (*n* = 23)	Yes
Gabriel *et al.* (2015)	*M* (*SD*) = 9.9 (1.9) years (*n* = 15)	*M* (*SD*) = 9.8 (1.8) years (*n* = 15)	No
Gabriel *et al.* (2012)	*M* (*SD*) = 10.3 (1.6) years (*n* = 15)	*M* (*SD*) = 10.4 (1.6) years (*n* = 15)	No
Hedenius *et al.* (2011)	*M* (*SD*) = 10.1 (1.1) years (*n* = 21)	*M* (*SD*) = 9.9 (1.1) years (*n* = 27)	Yes
Hsu and Bishop (2014)	*M* (*SD*) = 8.7 (1.3) years (*n* = 48)	Age-matched *M* (*SD*) = 8.8 (0.9) years (*n* = 20) Grammar-matched *M* (*SD*) = 5.7 (0.9) years (*n* = 28)	Yes for age-matched, no for grammar-matched
Lukács and Kemény (2014)	*M* (*SD*) = 9.1 (1.3) years (*n* = 29)	*M* (*SD*) = 9.1 (1.3) years (*n* = 87)	Yes
Lum and Bleses (2012)	*M* (*SD*) = 7.7 (0.8) years (*n* = 13)	*M* (*SD*) = 7.9 (0.7) years (*n* = 20)	No
Lum, Gelgic, *et al.* (2010)	*M* (*SD*) = 7.1 (0.9) years (*n* = 14)	*M* (*SD*) = 7.0 (0.8) years (*n* = 15)	Yes
Lum *et al.* (2012)	*M* (*SD*) = 9.8 (0.7) years (*n* = 51)	*M* (*SD*) = 9.9 (0.7) years (*n* = 51)	Yes
Mayor-Dubois *et al.* (2014)	*M* (*SD*) = 10.1 (1.8) years (*n* = 18)	*M* (*SD*) = 10.0 (1.6) years (*n* = 65)	Yes
Sengottuvel and Rao (2013)	*M* (*SD*) = 10.1 (1.8) years (*n* = 17)	*M* (*SD*) = 9.5 (1.2) years (*n* = 23)	Yes
Sengottuvel and Rao (2014)	*M* (*SD*) = 9.8 (1.7) years (*n* = 22)	*M* (*SD*) = 10.4 (2.0) years (*n* = 34)	Yes
Tomblin *et al.* (2007)	*M* (*SD*) = 15.0 (0.60) years (*n* = 38)	*M* (*SD*) = 14.76 (0.64) years (*n* = 47)	Yes

Note. SLI = specific language impairment; SRT = serial reaction time; TD, typical development.

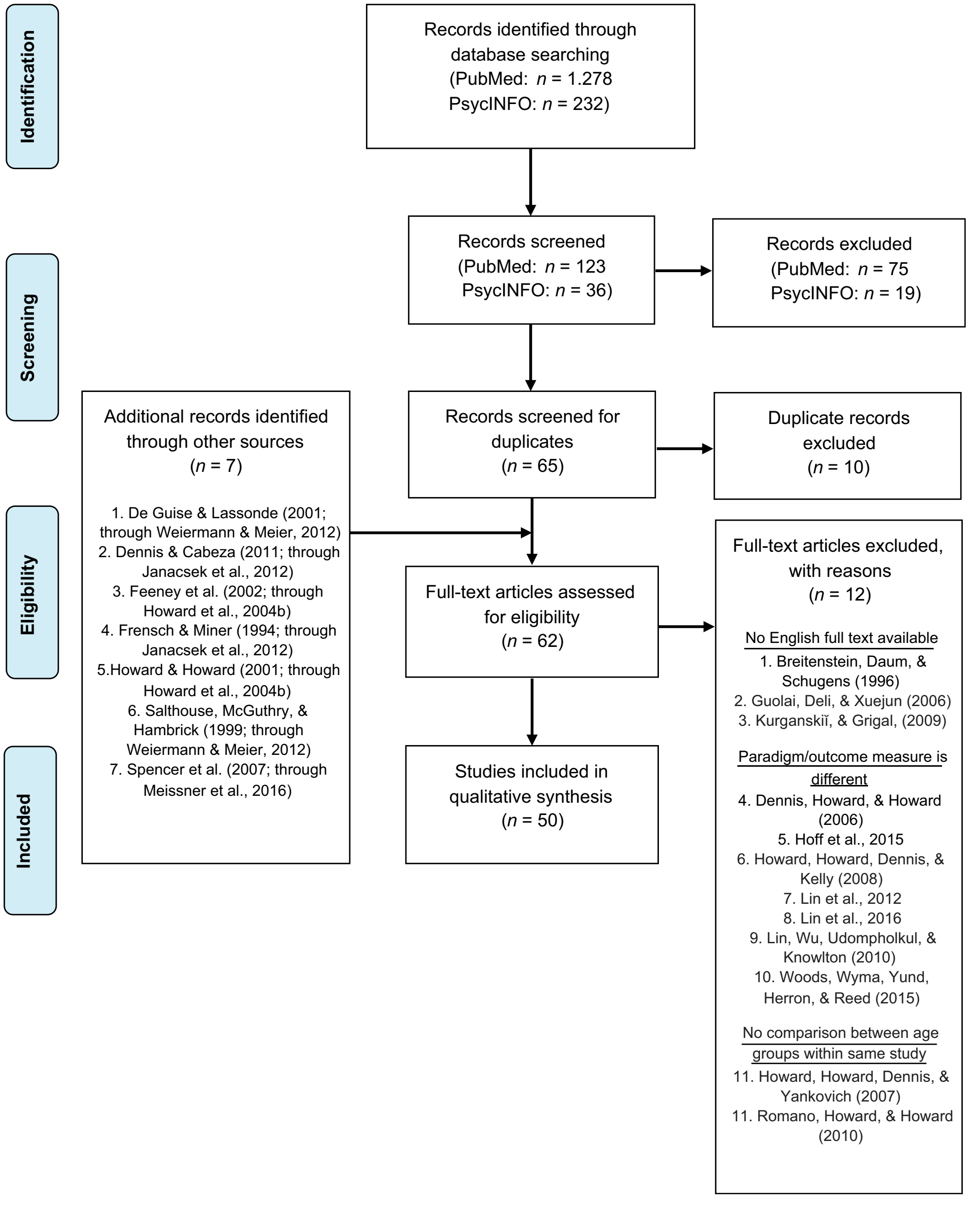

Figure 2. PRISMA flow chart for the systematic literature search for procedural learning across a typically developing lifespan.

2014), and three studies reporting higher accuracies for older adults (i.e., Bo, Jennett, & Seidler, 2012; Howard & Howard, 1989, 1992).

In summary, 17 of 50 studies have concluded that procedural learning measured by the SRT task is relatively stable across lifespan. However, subtle age differences in raw RTs and accuracy have been reported too, which might imply age-related changes in procedural learning.

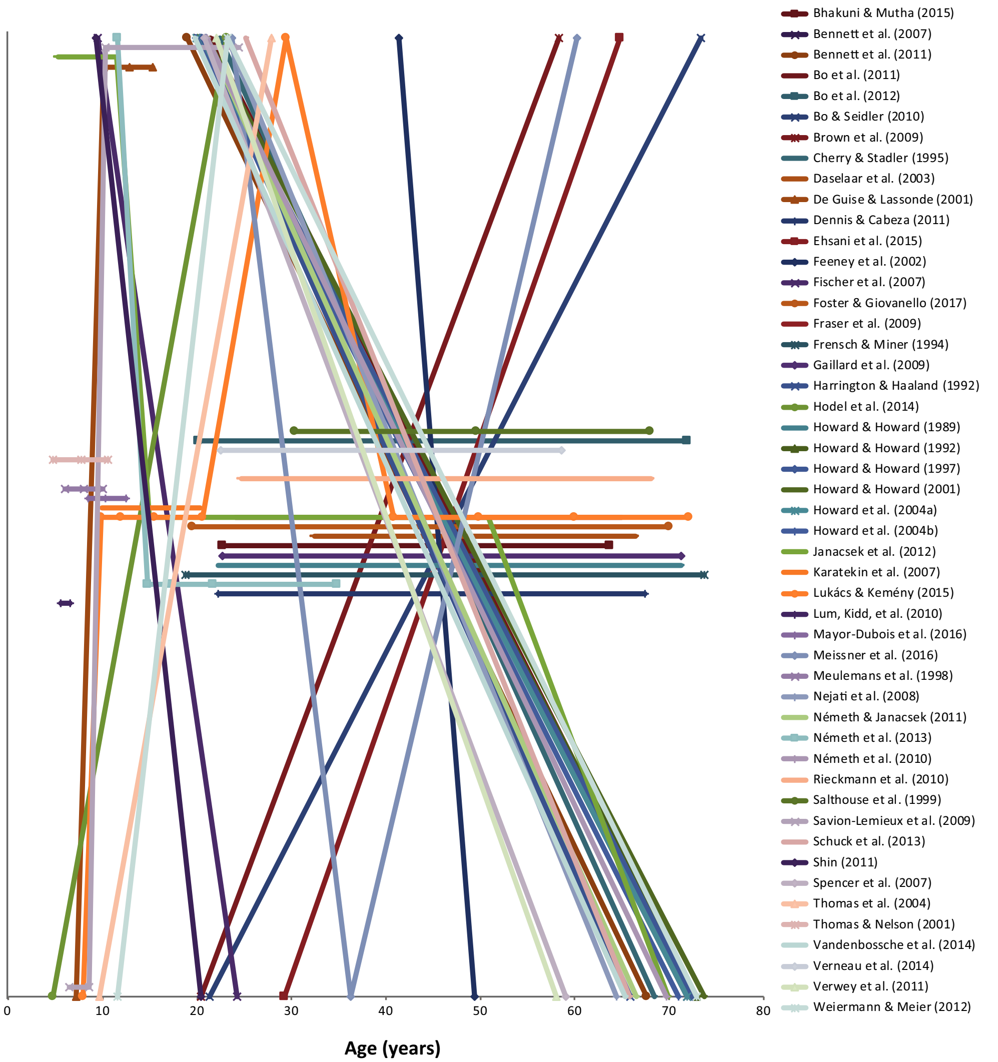

Figure 3. Graphical illustration of the direction of age effects in online procedural learning during the lifespan found in TD, with age (years) on the *x*-axis and procedural learning with a fictive value on the *y*-axis. The direction of the lines reflects the study outcome; for example, a downward line reflects a decline. Each study is represented only once, with each data point reflecting the mean age or weighted mean age in case of multiple experiments. One study (Curran, 1997) did not report the mean age of one age group and hence could not be included in the illustration.

Empirical evidence for models of age-related changes (Models 2a and 2b)

Thirty-three studies have reported age-related changes in procedural learning (see Table 2), 10 of which included children which were particularly interesting given Model 2a and Model 2b only differ with regard to the developmental trajectory during childhood (and not during advanced ageing). Specifically, Model 2a predicts an increase in procedural learning during childhood, whereas Model 2b predicts a strong procedural learning system present from early childhood on. Relating the findings to these models is, however, not that straightforward. Whether findings support Model 2a or Model 2b depends largely on whether or not authors corrected for baseline RT when interpreting their results.

Several studies with child groups support Model 2a, with normalized (i.e., baseline-corrected) RT data and accuracy measures of procedural learning strengthening from childhood to young adulthood (i.e., Hodel, Markant, Van Den Heuvel, Cirilli-Raether, & Thomas, 2014; Lukács & Kemény, 2015; Thomas *et al.*, 2004), extended by similar findings in raw RT data of one study (Savion-Lemieux, Bailey, & Penhune, 2009). Two studies have reported age-related changes depending on task characteristics (De Guise & Lassonde, 2001; Shin, 2011). In the largest study (N = 247), Lukács and Kemény (2015) have investigated age-related changes in skill learning on three different tasks, including the SRT task. Although the raw RT data showed a pattern in line with Model 2b, the normalized RT data showed that the adolescents and young adults performed best on all three tasks, with a peak in performance between 18 and 35 years old. The authors argue that the normalized data give the best reflection of the procedural learning abilities.

Model 2b was originally developed based on the raw RT data of the study conducted by Janacsek *et al.* (2012). In their large study (N = 421), five child age groups and four adult age groups were compared. Findings suggested a stronger learning effect in the young groups (4- to 12-year-olds) which gradually declined over the older groups (14- to 85-year-olds). These findings were confirmed by a second paper of the same group, using partly the same group of participants (Németh, Janacsek, & Fiser, 2013), and are in line with a previous study (Fischer, Wilhelm, & Born, 2007). Janacsek *et al.* (2012) have also shown that normalizing their RT data revealed the bell-shaped pattern in accordance with Model 2a. However, these authors argued that the differences in processing speed are inherent aspects of development and that normalized data would therefore be difficult to interpret. In summary, it seems that the two larger studies both support Model 2a when the RT data are normalized and Model 2b when raw RTs are used.

In the reviewed studies regarding cognitive ageing (n = 23), baseline speed differences also seem to influence the interpretation of findings, and there is an additional focus on accuracy data and consolidation (rather than online learning) findings. The effect of baseline speed is reflected by the differential findings for raw compared to normalized RT data. Several studies (n = 8) have concluded an ageing deficit on other measures than RTs during the task and reported equal performance in younger and older adults in raw RT data (Bennett, Howard, & Howard, 2007; Bennett, Madden, Vaidya, Howard, & Howard, 2011; Dennis & Cabeza, 2011; Németh & Janacsek, 2010; Spencer, Gouw, & Ivry, 2007; Weiermann & Meier, 2012) or even stronger learning effects in older adults (Bo & Seidler, 2010; Brown, Robertson, & Press, 2009), whereas other studies have shown an age deficit in normalized RT findings (Lukács & Kemény, 2015; Vandenbossche, Coomans, Homblé, & Deroost, 2014). However, a large number of studies (n = 12) using raw RT measure have reported ageing deficits too (Feeney, Howard, & Howard, 2002; Howard & Howard, 2001) and most of them even despite baseline speed differences (Bo, Peltier, Noll, & Seidler, 2011; Ehsani, Abdollahi, Bandpei, Zahiri, & Jaberzadeh, 2015; Harrington & Haaland, 1992; Howard, Howard, Dennis, Yankovich, & Vaidya, 2004; Howard, Howard, Japikse, *et al.*, 2004; Janacsek *et al.*, 2012; Nejati, Garusi Farshi, Ashayeri, & Aghdasi, 2008; Németh, Janacsek, Londe, *et al.*, 2010; Schuck *et al.*, 2013; Verwey, Abrahamse, Ruitenberg, Jiménez, & de Kleine, 2011). Impaired accuracy in older adults has led to conclusions of age-related deficits in procedural learning despite intact raw RT improvements (Bennett *et al.*, 2007, 2011). Other studies have concluded specific impairments in consolidation in older adults, while online learning is intact or even stronger (Ehsani *et al.*, 2015; Németh & Janacsek, 2010; Spencer *et al.*, 2007). One study has found intact RT performance, but differences in brain activity between younger and older adults (Dennis & Cabeza, 2011). Finally, one study using yet a different measure of RT improvements (percentages) has concluded that there are procedural learning deficits in middle-aged adults compared to younger and older adults (Meissner, Keitel, Südmeyer, & Pollok, 2016).

Summary of findings in typical development

In summary, the majority of empirical evidence is in favour of an age variance model of procedural learning across the lifespan. Inconsistencies in findings can be largely explained by how procedural learning is measured. The use of raw RT data predominantly supports Model 2b, whereas the use of normalized RT data supports Model 2a. A substantial number of studies on ageing have shown that raw RT data can be sensitive for detecting ageing-related decrements even when baseline speed differences are present, supporting the use of raw RT data rather than normalized RT data.

Atypical development

It has been suggested that a deficit in procedural learning could account for the core deficits in social and communication skills characterizing ASD (e.g., Mostofsky, Goldberg, Landa, & Denckla, 2000), and for the grammar deficits found in SLI (e.g., Ullman & Pierpont, 2005), and that perhaps such a deficit could be compensated for by declarative mechanisms during development (Klinger, Klinger, & Pohlig, 2007; Lum *et al.*, 2014; Ullman & Pullman, 2015). However, findings of a recent meta-analysis suggest that a procedural learning deficit underlies the deficits in SLI, but not in ASD (Obeid *et al.*, 2016).

Empirical evidence: ASD

Our systematic literature search regarding procedural learning in ASD led to 11 studies using the SRT task (see Figure 4 for PRISMA flow chart and Table 3). None of the studies included different age groups, making direct comparisons between age groups across the lifespan impossible. Claims on a developmental trajectory are further hampered by the very broad age ranges and similarity in mean ages (10- to 11-year-olds) in most ASD studies. However, there are a few adult studies and between-study differences that might be informative.

The majority of the reviewed studies have found that procedural learning is intact in ASD, with only four studies supporting a deficit (Gordon & Stark, 2007; Mostofsky *et al.*, 2000; Sharer, Mostofsky, Pascual-Leone, & Oberman, 2016; Travers, Kana, Klinger, Klein, & Klinger, 2015). However, in the study of Sharer *et al.* (2016), this deficit was only related to the use of visual feedback in a generalization task, not to overall learning. Although one study has found a deficit in young adults (Travers *et al.*, 2015), a previous study with young adults revealed intact procedural learning (Travers, Klinger, Mussey, & Klinger, 2010). One of the older studies supporting a procedural learning deficit in ASD (Mostofsky *et al.*, 2000) has been criticized for using a slow repetition of sequences, which makes it more likely that a person develops declarative knowledge during the task (Brown, Aczel, Jiménez, Kaufman, & Grant, 2010; Destrebecqz & Cleeremans, 2003).

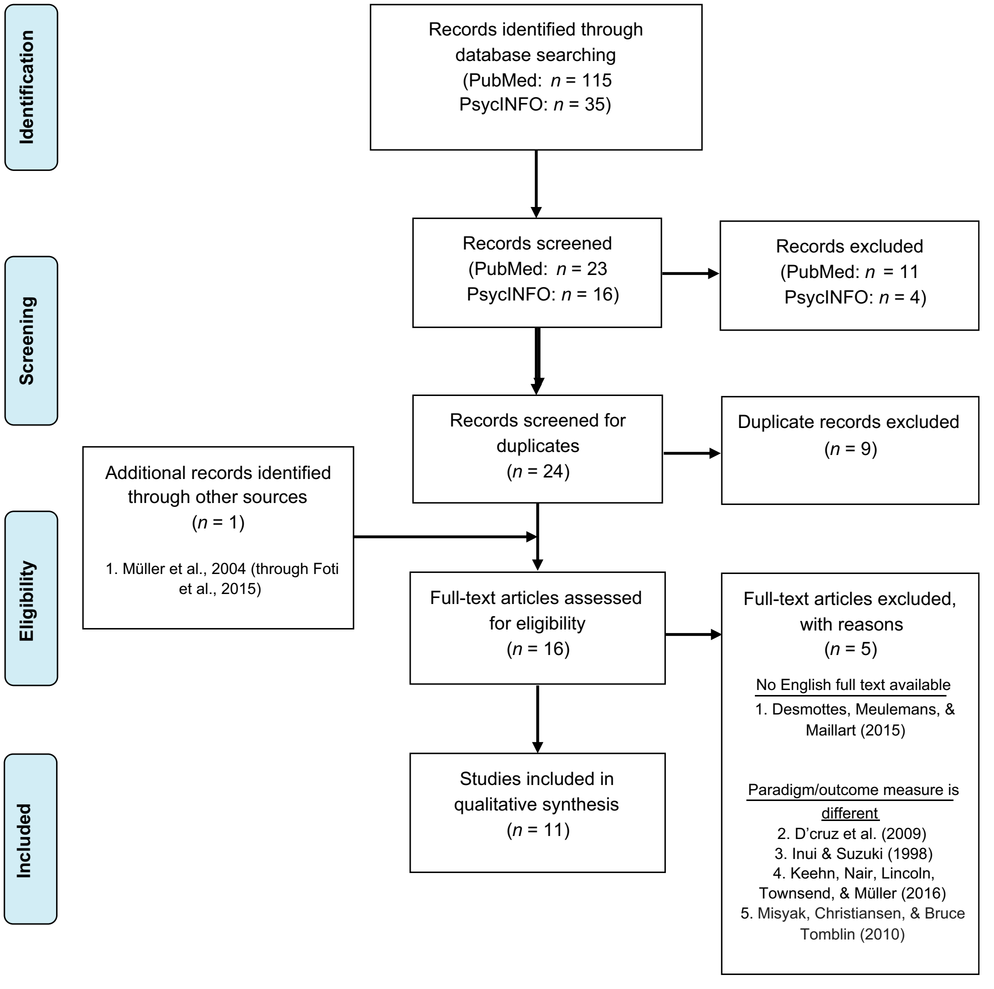

Figure 4. PRISMA flow chart for the systematic literature search for procedural learning in autism spectrum disorder.

Declarative strategies can increase or decrease performance, depending on the cognitive demands of a task (e.g., Howard & Howard, 2001), and hence, enhanced declarative strategies in the ASD participants could have hindered their performance on complex tasks.

The issue of baseline speed is also critical in ASD studies, with baseline speed often reported to be slower in ASD (e.g., Barnes *et al.*, 2008; Németh, Janacsek, Balogh, *et al.*, 2010; Travers *et al.*, 2010), although not in all studies (i.e., Sharer *et al.*, 2015, 2016). However, all but one study have reported raw RT results (with the exception of the study by Izadi-Najafabadi, Mirzakhani-Araghi, Miri-Lavasani, Nejati, & Pashazadeh-Azari, 2015; in which it is unclear whether and how RT data were normalized). Interestingly, two studies examined normalized data as well as raw RT data and found similar results (Barnes *et al.*, 2008; Brown *et al.*, 2010). Accuracy has also been analysed in most studies and has consistently confirmed the intact learning found using RT data (Barnes *et al.*, 2008; Brown *et al.*, 2010; Müller, Cauich, Rubio, Mizuno, & Courchesne, 2004; Németh, Janacsek, Balogh, *et al.*, 2010; Sharer *et al.*, 2015, 2016; Travers *et al.*, 2010).

Empirical evidence: SLI

A systematic search for literature regarding procedural learning in SLI led to the inclusion of 18 studies (see Figure 5 for PRISMA flow chart and Table 4). Similar to the ASD literature, no studies have included multiple age groups and most studies focused on children in the age of 9–11 years, making interpretations of the developmental trajectory difficult.

Overall, the majority of the reviewed studies (n = 14) have reported a procedural learning deficit in SLI, although several individual studies concluded that procedural learning is intact. Comparable procedural learning capacities for children with SLI and a TD group were found in three studies by Gabriel and colleagues and one other study (Gabriel, Maillart, Guillaume, Stefaniak, & Meulemans, 2011; Gabriel, Meulemans, Parisse,

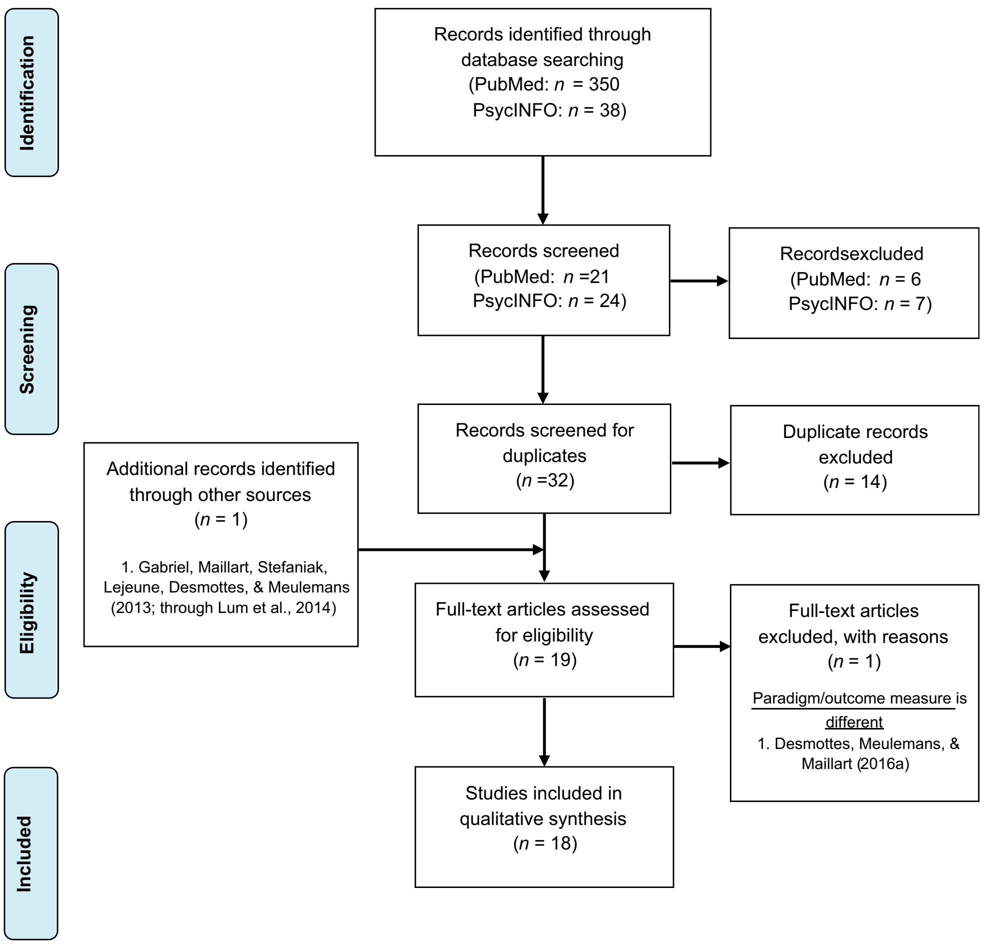

Figure 5. PRISMA flow chart for the systematic literature search for procedural learning in specific language impairment.

& Maillart, 2015; Gabriel, Stefaniak, Maillart, Schmitz, & Meulemans, 2012; Lum & Bleses, 2012), although one other study by the same group using a more complex task did reveal deficits (Gabriel *et al.*, 2013). Relatively intact learning during the initial task has also been found in two other studies, where impaired performance was found only in later tasks that were intended to assess consolidation (Desmottes, Maillart, & Meulemans, 2016; Hedenius *et al.*, 2011).

The variation in the specific measures employed can only partially account for the inconsistent findings. Baseline speed differences have also been reported in the SLI literature, with some studies showing slower baseline speed in SLI compared to TD children (Desmottes, Meulemans, & Maillart, 2016b; Gabriel *et al.*, 2012, 2013; Hsu & Bishop, 2014; Lukács & Kemény, 2014; Mayor-Dubois, Zesiger, Van der Linden, & Roulet-Perez, 2014; Tomblin, Mainela-Arnold, & Zhang, 2007), whereas other studies did not find a difference (Gabriel *et al.*, 2011, 2015; Sengottuvel & Rao, 2013). Two studies have found intact procedural learning when using raw RT data but a deficit when employing normalized RT data (Gabriel *et al.,* 2013; Lukács & Kemény, 2014), but one other study reported intact procedural learning for both raw and normalized RTs (Gabriel *et al.*, 2015). Furthermore, several studies that analysed raw RTs only also reported deficits (Hsu & Bishop, 2014; Mayor-Dubois *et al.*, 2014; Sengottuvel & Rao, 2013, 2014; Tomblin *et al.*, 2007). Higher error rates in SLI have been reported in some (Gabriel *et al.*, 2012, 2015; Lum, Gelgic, & Conti-Ramsden, 2010) but not all studies (Desmottes *et al*., 2016b; Gabriel *et al.*, 2011; Hsu & Bishop, 2014; Lum & Bleses, 2012; Lum, Conti-Ramsden, Page, & Ullman, 2012).

Summary of findings in atypical development

In summary, the majority of the reviewed studies on ASD do not seem to find evidence for a procedural learning deficit, even when differences in baseline speed are accounted for. The reviewed studies on SLI, however, do suggest a procedural learning deficit, which seems more pronounced in younger than older children. However, the ASD and SLI studies so far are very limited in terms of age groups. As a result, the findings could not be interpreted in terms of a developmental trajectory.

General discussion

Procedural learning in typical development: age-related changes

The overall findings of this systematic review support age-related changes in procedural learning across the lifespan in TD. Findings of age-related changes in learning effects are very similar across two large studies (i.e., Janacsek *et al.*, 2012; Lukács & Kemény, 2015). However, the authors' interpretation of these findings in terms of the developmental trajectory differs, due to a lack of consensus on how to deal with age-dependent differences in baseline motor speed. While some authors adjust for these differences by normalizing the data, for example, by applying a z-transformation (Lukács & Kemény, 2015), others argue that the raw data are the best reflection of learning (Janacsek *et al.*, 2012). The latter view is supported by findings of age deficits in raw RT data in young children and older adults despite the presence of slower baseline RTs. Overall, the raw RT data seem to show a pattern in line with Model 2b, whereas the z-transformed data reveal a bell-shaped pattern in line with Model 2a. Thus, although there is clear evidence for age-related changes in procedural learning, the exact trajectory during childhood seems to depend on how this learning is measured.

Procedural learning in atypical development: intact in ASD and impaired in SLI

We aimed to extend these findings of age-related changes in TD to findings of procedural learning in atypical development in ASD and SLI. Overall, studies support intact procedural learning in ASD and a deficit in SLI. A few inconsistencies between studies were found for both disorders, with four of 11 studies showing impaired procedural learning in ASD and four of 18 studies showing intact procedural learning in SLI. These inconsistencies could not be explained by differences in age groups across these studies. Differences in outcome measures, such as raw versus normalized RT data, could also not fully account for these inconsistencies, as these differences were not consistently linked to the different conclusions. Furthermore, any modelling of the developmental trajectory of procedural learning in these disorders was severely hindered by the lack of variety in age groups included in the studies, with most studies focusing on 9- and 10-year-olds. Taken together, these findings call for more studies including young children, adolescents, and adults with ASD and SLI, preferably including multiple age groups within the same study design.

These findings of intact procedural learning in ASD and impaired procedural learning in SLI are in line with the three meta-analyses on these topics (Foti *et al.*, 2015; Lum *et al.*, 2014; Obeid *et al.*, 2016). The role of age in inconsistent study findings has also been brought forward in Lum's meta-analyses on SLI (Lum *et al.*, 2014). The authors have found that between-study differences in effect sizes are caused by variation in the age of participants and characteristics of the SRT task. More specifically, the effect sizes related to the difference in task performance between SLI and TD participants were smaller for older than for younger children. This strongly supports an age variance model of procedural learning (Model 2a or 2b). However, Obeid *et al.* (2016) failed to replicate this age effect in their meta-analyses on SLI and ASD. Furthermore, Lum *et al.* (2014) suggested that the age effects they found might result from the older children being better than the younger children at compensating for the procedural learning deficit using declarative mechanisms.

The role of declarative learning on the SRT task

A factor that may influence findings in both typical and atypical development is declarative (or intentional) learning. Learning on the SRT task – as well as on other procedural learning paradigms – is not always purely procedural in nature, but can be 'contaminated' by declarative learning, as indicated by the substantial number of participants who can verbally describe what they have learnt after the task (e.g., Haider & Rose, 2007). Declarative learning strategies might affect learning performance differently, depending on cognitive capacity. For example, in the cognitive ageing literature evidence has been found that young adults benefit from declarative learning strategies, whereas older adults are actually hindered by these strategies (Howard & Howard, 2001). Here, young adults were instructed to learn on an SRT task (i.e., declarative learning) and performed better than their peers who did not receive this instruction (i.e., procedural learning). However, this pattern was reversed in older adults with those instructed performing worse than those who were not. In children, it is believed that the declarative learning system becomes more efficient and more prominent during development (e.g., Janacsek *et al.*, 2012; Mayor-Dubois *et al.*, 2016). Hence, older children may rely more on this declarative system, which could lead to better performance when task demands are low, but to worse performance when task demands are high, irrespective of their procedural learning ability.

Similarly, in ASD and SLI it has been suggested that the declarative system is more easily triggered, perhaps as a compensatory mechanism for procedural learning deficits (e.g., Klinger *et al.*, 2007; Lum *et al.*, 2014; Romero-Munguía, 2008; Ullman & Pullman, 2015). This could lead to increased performance on simple tasks and decreased performance on more complex tasks (e.g., Howard & Howard, 2001). In ASD, one study found intact performance in ASD on a common (uninstructed) SRT task, but worse performance than TD when information about the sequence was given, hence suggesting impaired declarative rather than procedural learning (Izadi-Najafabadi *et al.*, 2015). Similarly, (subtle) impairments in explicit learning performance in ASD compared to TD were found in the study of Brown *et al.* (2010). In SLI, Lum *et al.* (2014) have suggested that a more developed compensatory mechanism in older children might account for the smaller effect sizes of a procedural learning deficit compared to younger children. However, another plausible explanation for a more pronounced deficit in younger compared to older children with SLI is that procedural learning efficiency follows a developmental trajectory similar to that in TD (Model 2a).

Heterogeneity in study characteristics

A limitation of the current systematic reviews is that only qualitative reviews were conducted. Our first aim was to establish which model in TD is most accurate by giving a full overview of the existing literature. This could also have been done by carrying out a quantitative meta-analysis, but this would not have been straightforward, because the reviewed studies showed large heterogeneity in methods. Sources of heterogeneity included which effect was studied and which dependent variable was examined. For example, some studies based their conclusions on performance changes over time (e.g., an effect of trial block), other studies focused on an effect of type of stimulus (e.g., low- vs. high-probability stimuli), and yet other studies were primarily directed at assessing performance during a later stage, examining consolidation or retrieval rather than online learning. Dependent variables to measure learning included raw RTs, normalized RTs, and accuracy. Currently, it seems that the choice of dependent variable (particularly raw vs. normalized RTs) largely determines which model is most supported (see Janacsek *et al.*, 2012; Lukács & Kemény, 2015). Although a meta-analysis could at least partially deal with this complexity by, for example, adding dependent variables as a moderator, it would not be a straightforward procedure and interpreting the findings would be complicated. However, we do encourage future studies to conduct this type of research, and we hope that the current study can serve as a source of information regarding the current heterogeneous state of the literature. With regard to atypical development, we have added to the existing meta-analyses regarding ASD and SLI data (i.e., Foti *et al.*, 2015; Lum *et al.*, 2014; Obeid *et al.*, 2016) by taking into account studies that were previously not included.

Conclusions and scientific and clinical implications

In conclusion, age-related changes are found in procedural learning during TD. Overall, findings in ASD suggest intact procedural learning, whereas findings in SLI suggest a deficit. Inconsistent findings across studies can only be partly explained by the use of different outcome measures. The compensatory role of a declarative learning mechanism has also been suggested to influence findings, in both typical and atypical development (e.g., Howard & Howard, 2001; Klinger *et al.*, 2007; Lum *et al.*, 2014). Future research should address the role of declarative learning on SRT task performance. Furthermore, there is a need for studies involving and comparing young children, adolescents, and adults in atypical development, because these groups are currently underrepresented. Combined with our knowledge concerning the developmental trajectory of procedural learning in TD, future studies including multiple age groups could clarify, for example, whether the current findings regarding procedural learning in SLI reflect a deficit or a delay. The answer to this question would have specific clinical implications.

A severe procedural learning deficit would call for compensation by the declarative learning mechanism. In grammar learning, for example, this could mean teaching grammar rules explicitly, rather than expecting a child to pick up certain rules implicitly by reading a book. Similarly, social rules can be taught explicitly. If, on the other hand, procedural learning is intact (such as most likely in ASD) or present but delayed (perhaps in SLI), the preferable approach could be to stimulate this procedural learning system. Such an approach may be found in errorless learning, referring to training a skill while minimalizing error making by adjusting the task (e.g., Terrace, 1963). This is often done by creating a desired situation, followed by gradually removing prompts or cues from the situation (e.g., Mueller, Palkovic, & Maynard, 2007). In ASD, this approach has been successfully applied to improve engagement in social interaction, using fading prompts of a scripted social interaction (Stevenson, Krantz, & McClannahan, 2000). Errorless learning has also been applied to school interventions in ASD (Mueller *et al.*, 2007) and to the language domain in aphasia (Fillingham, Hodgson, Sage, & Lambon Ralph, 2003). Thus, a severe procedural learning deficit could be compensated for by declarative learning, whereas a less severe deficit or an underused procedural learning mechanism would call for stimulation, for example, through errorless learning techniques.

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Appendix: Search terms

Search terms used for a systematic search of literature on procedural learning in TD, ASD, and SLI

PUBMED/PSYCINFO TD: ((procedural learning OR serial reaction time OR alternating serial reaction time) AND (development or lifespan or ageing)).

PUBMED/PSYCINFO ASD: ((procedural learning OR serial reaction time OR alternating serial reaction time) AND (autism OR autism spectrum disorder OR autistic disorder OR child development disorder OR pervasive developmental disorder OR Asperger Syndrome)).

PUBMED/PSYCINFO SLI: ((procedural learning OR serial reaction time OR alternating serial reaction time) AND (specific language impairment OR primary language impairment OR language impairment OR developmental language impairment OR speech impairment OR communication impairment OR verbal impairment OR language delay OR developmental language delay OR communication delay OR speech delay OR verbal delay OR language disorder OR expressive language disorder OR receptive language disorder OR mixed language disorder OR communication disorder OR speech disorder OR verbal disorder)).