Short title: **Somatosensation and typical development**

Descriptive title: **Does somatosensation change with age in children and adolescents? A systematic review**

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Abstract

Background: Somatosensory modalities, such as touch, proprioception and haptic ability greatly influence the achievement of developmental milestones for children. Describing somatosensory impairment, natural variability and typical or expected developmental changes across age groups will help establish frameworks for intervention in clinical populations. This systematic review aimed to determine how different somatosensory modalities develop across childhood into adolescence to use as a point of reference for children at risk of somatosensory impairment.

Methods: Searches of 5 electronic databases were undertaken through EBSCO-host (MEDLINE, CINAHL, PsycINFO, SPORTDiscus and ERIC) for studies measuring at least one somatosensory modality in typically developing individuals between birth and 18 years and analysed by age. Characteristics of studies were collected including country of origin, sample size, demographics and outcome measure used. Quality assessment and data extraction were performed by two independent reviewers.

Results: Twenty three cross-sectional studies were included from a total of 188 articles retrieved: 8 examined aspects of touch, 5 proprioception, and 10 haptic ability. Variability of study designs and variation in assessment tools precluded any formal meta-analysis.

Conclusions: Somatosensation matures through childhood into adolescence however, the present review found the pattern of somatosensory development varied depending on the assessment tool used and the aspect of somatosensation being measured, making it difficult to describe typical performance. There is a need for comprehensive assessment batteries to measure the somatosensation, including

touch, proprioception and haptic ability, of children at risk of somatosensory impairment to aid in the development of effective interventions.

Introduction

Everyday functioning is dependent on the ability to meet the sensory and motor demands of an ever changing environment (Ben-Sasson et al., 2009; Lundy-Ekman, 2002). A child relies on the sensation of touch for precision and dexterity, proprioception for hand control and gross motor function, and haptic ability to efficiently explore objects with their hands (Kalagher & Jones, 2011b; Marieb & Hoehn, 2007). The somatosensory system allows registration and characterisation of touch and further tactile exploration provides perceptual information about external objects and surfaces (Dijkerman & Haan, 2007). Touch is a multifaceted construct and we have employed a previously developed framework to organise our thinking about the various terms of reference for touch.

The framework includes two domains; tactile registration and tactile perception (Auld, Ware & Boyd, 2012). Tactile registration is the basic initial processing of stimuli and/or sensing of surfaces and can include terms such as touch sensitivity, tactile sensitivity; and touch threshold or threshold detection which is described as the minimal external stimulus that produces excitation of a cutaneous receptor (Weinstein, 1993; Riquelme et al., 2011; Bell-Krotoski et al., 1995). Tactile perception allows interpretation and understanding of stimulus such as location, timing and identification (i.e. what the

stimulus is) (Auld, Boyd, Moseley & Johnston 2011). Tactile perception may include terms such as tactile spatial acuity or tactile spatial resolution which is the ability to perceive the fine structure of a surface pressed against the finger (Peters & Goldreich, 2013; Bleyenheuft et al., 2006); tactile localisation which is the ability to indicate the location of a stimulus on the skin (Yoshioka et al., 2013); and tactile discrimination which is the ability to distinguish between different surface textures (Dunn et al., 2013; Carey, Matyas & Oke, 2002).

All aspects of touch are important for calibrating grasp and preventing objects from slipping, discriminating between different textures and in locating the origin of sensations within the immediate environment (Bremner et al., 2008; Eliasson, 2006). Disruptions in tactile registration and perception can impact dextral performance and everyday activities (Carey et al., 2002; Krumlinde-Sundholm & Eliasson, 2002).

Proprioception is the sense of the movement and position of the body, and in particular the limbs (Stedman's medical dictionary, 2008). The term proprioception includes the static component of limb or joint position sense (Bremner et al., 2013) and the dynamic component of sensing movement through kinaesthesia (World Health Organisation, 2001). The amalgamation of kinesthesia and limb position sense assists in proprioceptive localisation of the hand (Contreras-Vidal, 2006). Research consistently reports a clear link between proprioception and hand function, with proprioception affecting all gross motor and fine motor skills (Bumin & Kavak, 2010; Stillman, 2002). Proprioception is therefore important for education as it affects pencil grip and application of pressure (Bumin &

Kavak, 2010), keyboard skills (Rao et al., 2000) and is central to the execution of goal directed action through postural control (Viel et al., 2009).

Haptic ability is often referred to as haptic perception (Ballesteros et al., 2005; Gori et al., 2012; Kalagher & Jones, 2011a, 2011b) or stereognosis (Auld et al., 2012), and terms such as dynamic touch (Fitzpatrick & Flynn, 2010; Kloos & Amazeen, 2002), gnostic hand function (Van Grunsven et al., 2003), or haptic object recognition (Carey, 2012) are often used interchangeably or defined as part of haptic ability. In this review we will principally use haptic ability to encompass the aforementioned subset terms for ease of reporting. It is important to note that although touch and proprioception influence haptic ability and are important for efficient exploration of objects (Dunn et al., 2013) haptic ability relies on higher order cognitive processes and involves a complex integration of these somatosensory inputs as well as effective haptic exploratory procedures (Carey, 2012). Identification of objects using haptic ability requires touch and in-hand object manipulation to extract information such as texture, hardness, temperature, size, weight and shape of an object (Lederman & Klatzky, 2009). Haptic ability is critical to haptic object recognition, because the way an individual moves his or her hands, and their choice of exploratory procedures, determines the sensory information extracted and ultimately the meaning that is derived from an object (Jones & Lederman, 2006; Kalagher & Jones, 2011b). A child's learning and early development is influenced by their level of haptic ability (Ballesteros et al., 2005; McLinden, 2004).

Typical development is underpinned by an intact somatosensory system with unimpaired functioning of touch, proprioception and haptic ability (Pehoski, 2006; Royeen & Lane, 1991). Typical functional somatosensation provides a benchmark against which to compare clinical populations who are known to experience somatosensory deficits in the hands (Auld et al., 2012; Clayton, 2003; Cooper et al., 1995). From current literature we know that between 31 to 97% of children with cerebral palsy assessed experienced deficits in touch registration, proprioception and/or touch perception and stereognosis (Auld et al., 2012; Cooper et al., 1995; Wingert et al., 2008). Identifying and describing somatosensory deficits is crucial in understanding the impact of impairment on hand function and, as a result, establishing frameworks for intervention (Carey, 2012). Little is known about the developmental trajectory of somatosensation in typically developing children and adolescents despite the publication of sensory and motor developmental milestones (Case-Smith, 2010; Vroman, 2010). The objective of the current systematic review was to identify how somatosensory modalities mature in typically developing children from birth to 18 years to use as a point of reference for children at risk of somatosensory impairment.

Methods

A search of five electronic databases was undertaken to identify studies that met *a priori* inclusion criteria. Databases were chosen based on their relevance to the Participants, Interventions, Comparisons, Outcome and Study design (PICOS) model that formulated the review objective (Moher et al., 2009). The relevant PICOS elements used to determine the eligibility of studies were:

Participants: Typically developing children from birth to 18 years with no history of neurological,

sensory, sensorimotor, cognitive, psychiatric, psychological or physical impairments. *Comparisons:* Changes across age, birth to 18 years. *Outcomes:* Tactile, haptic and/or proprioceptive ability. *Study designs:* Any meeting inclusion criteria.

This review was conducted according to the Centre for Reviews and Dissemination Guidelines (Centre for Reviews and Dissemination, 2009) and is presented following the PRISMA statement for reporting systematic reviews and meta-analyses (Moher et al., 2009). Electronic resources were screened from 2002 via EBSCO-host (MEDLINE, Cumulative Index of Nursing and Allied Health Literature - CINAHL, PsycINFO, SPORTDiscus with Full Text and ERIC) to April 2015. Reference lists of relevant studies were also manually screened. Only studies published between 2002 and 2015 were included as this review aimed to answer the objective with maximal appreciation of current research designs and contemporary knowledge.

Articles were selected according to the following inclusion criteria: 1) study describes somatosensation in typically developing children aged between birth to 18 years analysed by age (including those selected as a comparison group to a clinical population); 2) comparison between two or more age groups; 3) description of functional aspects of touch, proprioception, or haptic ability for the hands and upper limb. Exclusion criteria were: 1) studies where confounding factors could not be eliminated, e.g., prior knowledge of outcome measure or influence of other sensory modalities, such as vision; 2) studies examining somatosensation of the lower limbs or trunk, sensory seeking, sensory processing or integration, visceral, vestibular, oral, auditory, olfactory or visual sensations.

Search term combinations included a population term (i.e., *typic* develop* child**) a sensory term (e.g. *propriocept**) and a descriptor (*change**). The selected search strategy was *sensation or propriocept* or haptic or haptic perception or haptic object recognition or touch or tactile or tactual or hand sensibility.fs AND child* or adolescen* or young adulthood or teenagers or young people or youth or typical* develop* AND Development* change or change* or maturation or age* or longitudinal.fs or follow-up or lifespan*. Searches were guided by a librarian who assisted with the formulation of the search strategy through truncation and explosion of text terms and selection of Boolean operators. The search strategy located many articles related to drugs, smoking and sensory-seeking behaviours that were irrelevant to this review due to the terms *adolescent**, *teenagers* and *youth*, however it was deemed appropriate to include these terms in order to maximise sensitivity.

Each paper was assessed for methodological quality and risk of bias by two independent reviewers using: a) 10 item checklist for quality of reporting and b) critical review of applicable criteria for quality of evidence. These methods were based on the assessment tool for quantitative studies developed by Kmet et al. (2004). The checklist was modified by removing irrelevant items such as allocation of clinical comparison groups or items related to interventional studies. The 10 item checklist enabled each reviewer to allocate a summary score (total sum / total possible sum of 20) and rating of strong, good, adequate or limited to describe the methodological quality of reporting items most significant to this review (Lee et al., 2008). In addition, two items were chosen from the Kmet checklist of methodological quality of evidence and summarised descriptively: Was the group appropriate for objectives? (e.g., socioeconomic status, demographic information or age); were the measurements of

outcomes resistant to bias? (e.g., psychometric properties reported or available). Item selection was based on what the results of the studies relevant to this review would be most vulnerable to and enabled detection of systematic bias. If the studies did not meet the criteria for quality of reporting or evidence they were excluded (Table 1).

Data extraction forms were developed prior to the literature search. Two authors independently reviewed each study and extracted the following data: first author, country of origin of study and sample (often comparison group), study design, sample size, age range, gender, somatosensory modality examined, outcome measure used and associated psychometric information and summary of results. The variability of included studies with respect to age range, method of measurement of somatosensation and, hence, the aspect of the modality under investigation, and the method of reporting results precluded any formal meta-analysis therefore the findings are summarised descriptively.

Results

The electronic and manual searches detected 188 articles, 27 cross sectional studies met the inclusion criteria¹. Four were subsequently excluded on account of poor methodology, the inability to eliminate the impact of confounding factors, such as prior knowledge of the somatosensory task, or because the required data could not be extracted at the group level (Table 1). The included studies investigated aspects of touch $n = 8$; proprioception $n = 5$; and haptic ability $n = 10$ (Figure 1). No systematic

¹ Please note 3 studies (Dunn et al., 2013; Dunn et al., 2015; Abu-Dahab et al., 2013) examined aspects of touch, proprioception and/or haptic ability in the same paper using the same population so therefore were counted multiple times across somatosensory categories.

reviews were identified. All 23 studies were cross sectional in design, with a combined total of 2,418 typically developing participants in which 749 were assessed for touch (age range = 3 - 18 years), 256 participants for proprioception (age range 3 - 18 years) and 1,413 participants for aspects of haptic ability (age range = 2.5 - 16 years). All participants met the criteria of typical development, 58% of the total participants were from the Americas (United States, Mexico/Columbia, Canada) and 38% were of European background (Belgium, France, Italy, Netherlands, Spain) and 4% from Australia.

Methodological quality of reporting summary scores ranged from adequate (11/20) to strong (17/20) (Table 2).

Touch

To measure touch sensitivity Riquelme et al. (2011) used standardised von Frey monofilaments (0.14-1.01mm) which have documented psychometric properties (Somedic Sales AB, Sweden). To measure tactile perception Abu-Dahab et al. (2013) used the Reitan-Kolve test of Finger Agnosia and Dunn et al. (2013; 2015) used the standardised Tactile Discrimination Test to measure tactile discrimination. Both measures reported robust psychometric properties for adults (Carey, Oke, & Matyas, 1997; Reitan & Wolfson, 1985). Bleyenheuft et al. (2006; 2010) employed the Grating Orientation Task (GOT) to measure tactile spatial resolution and Peters and Goldreich (2013) used the GOT to measure tactile spatial acuity. Original literature reports the GOT as a measure of tactile spatial acuity (Craig, 1999; Gibson and Craig, 2002) and also tactile spatial resolution (Johnson, 1981), and reports the terms interchangeably (Craig and Johnson 2000). The GOT has been validated in adults, but not children (Craig, 1999; Gibson and Craig, 2002). Yoshioka et al. (2013), measured tactile localisation using

testing procedures and stimuli designed specifically for their study, and did not report on psychometric validity.

The association with age varied with the aspect of touch measured. One study examined tactile registration and reported a positive effect of age however reported no statistically significant differences. Riquelme et al. (2011) showed touch sensitivity improved with age; touch thresholds in 6 - 10 years olds were greater (less sensitive) than adolescents (11 - 17 years).

Seven studies examined tactile perception and reported a positive effect of age with three studies reporting statistically significant differences. Bleyenheuft et al. (2010) reported scores for tactile spatial resolution were highly correlated with age. Calculated values for the GOT decreased (improved) with age from 4 to 17 years ($p < 0.001$) and stabilised at 10 to 16 years. Lowest tactile spatial resolution was reported for the youngest children (4 - 5 years). Similarly, in their 2006 study Bleyenheuft and colleagues reported a highly significant difference ($p < 0.001$) between 6 to 9 year olds and 10 to 16 year olds for tactile spatial resolution. Dunn et al. (2013) reported that children 6 years and younger (3 - <7) performed significantly less well ($p < .0001$) than the older age group (7 - <19) for tactile discrimination. Similarly, Dunn et al. (2015) described an increase in tactile discrimination as age increased with the older age group (7 - 12 years) outperforming the younger age group (3 - 6 years). Yoshioka et al. (2013) established that mean errors in tactile localisation decreased with age between 4 to 9 years and were stable thereafter. It was reported that 10 to 12 year olds reached an adult level of performance (0.02 of the hand length = average distance between the stimulus and

response locations with relation to hand length) compared to 4 to 6 year olds who demonstrated a large average error (.05–.08 of hand length) (Yoshioka et al., 2013). Abu-Dahab et al. (2013) reported an improvement in finger recognition as age increased with errors decreasing from 80% (5 - < 8 years) to 44% (8 - < 12 years). In contrast, Peters and Goldreich (2013) was the only study to report no significant effect ($p = 0.403$) of age on tactile spatial acuity for their participant sample aged 6 to 16 years.

Proprioception

Reported outcome measures for proprioception involved either programmed stimulation or electrically controlled devices, or therapist imposed movements of the upper limb. A digitising tablet and pen (WACOM InTuos™) was used by Contreras-Vidal (2006) to detect errors in proprioceptive localisation of the hand. No psychometric information was reported. Goble et al. (2005) used custom software and forearm plates designed to measure elbow joint rotation, indicating proprioceptively-guided movements through voltage output and Hay et al. (2005) used computer operated vibrators and targets during a serial pointing task. Goble et al. (2005) and Hay et al. (2005) reported that their testing procedure was based on previous research methodology, however no psychometric data were reported. Dunn et al. (2013) used the Brief Kinesthesia Test (Ayres, 1972; 1980; 1989) and Dunn et al. (2015) used an assessment battery including the Brief Kinesthesia Test, Wrist Position Sense Test and the Clinical Test of Wrist Position (Carey, Oke, & Matyas, 1996). The Wrist Position Sense Test reported robust psychometric properties for adults.

All five studies reported that proprioception improved with age and four reported statistical significance. Contreras-Vidal (2006) found a statistically significant effect of age for all dependent variables (movement time $p < .005$; end-point error $p < .001$; initial directional error $p < .05$). Constant & variable errors decreased as age increased from 5 to 10 years old. End-point error variability of the hand was largest for the youngest children (5 - 6 year old group) and did not differ within the older age groups (7 - 8 and 9 - 10 year olds). (Goble et al. (2005) reported matching errors significantly decreased as age increased ($p < .001$) with a mean absolute error of 6.2° for children (8 - 10 years) and 3.7° for adolescents (16 - 18 years). Errors made by children were also more variable and ranged from 0.1° - 20.8° compared to the adolescents where range of error was between 0.0° - 14.1° . Dunn et al. (2015) reported a decrease in error from 3 to 12 years for kinesthesia and also reported more variability in scores for 3 to 6 years olds compared to 7 to 12 year olds. Dunn et al. (2013) reported a statistically significant improvement ($p = .000$) between 3 to < 7 year olds and 7 to < 19 year olds for kinesthesia. Hay et al. (2005) reported a statistically significant effect of age for constant error ($p < .02$), variable error ($p < .01$) and position error ($p < .02$). Hay et al. (2005) also found highest variability in the youngest participants (5 years old) when performing the serial pointing task in extension, and poorest terminal accuracy at 5 years compared to the most accurate at ages 9 and 11 years. Variable & position errors decreased with increasing age with the lowest accuracy at age 5 years however in contrast the smallest constant error was made at age 5 and 11 years and the largest at age seven. Authors attributed the finding to young children's ballistic-type of movement control producing reasonably efficient end target accuracy. Goble et al. (2005) reported that although adolescents (16 - 18 years) had significantly

higher proprioceptive control of movement than children (8 - 10 years) ($p < 0.001$), the postural performance of 16 to 18 year olds did not match that of adults or individuals in late adolescence. Goble et al. (2005) also reported that pubertal growth and reorganisation of internal body schemas between ages 11 to 15 years in females and 13 to 17 years in males may temporarily decrease proprioceptive ability.

Dunn et al. (2015) was the only study to report on limb position sense at the wrist and reported a decrease in error from 3 to 12 years.

Haptic ability

Haptic ability was measured with a variety of different outcome measures. The ‘Haptic Test Battery’ used by Ballesteros et al. (2005) demonstrated satisfactory subtest reliability (Crombach’s α coefficient 0.54 to 0.88) and construct validity using factor analysis. Van Grunsven et al. (2003) reported acceptable agreement (weighted coefficient kappa .86 for left fingers, .78 for left thumb, .80 for right fingers, and .79 for right thumb), for test-retest reliability for the ‘Bottle test’, specifically designed for their study. Ardila et al. (2011) measured identification of objects, using the left or right hand, with the Sensory Perception (identification of objects) subtest of the Child Neuropsychological Assessment (Matute et al., 2007), which has documented external validity. Abu-Dahab used the Luria-Nebraska test of Stereognosis and did not report on the subtest’s psychometric properties (Golden, Purisch & Hammeke, 1979). Three studies used instruments reported in previous literature, however no psychometric data were reported, they included; novel category exemplars, the ‘matching to sample’

task (Kalagher & Jones, 2011a; 2011b), and Dunn et al. (2015) used The Brief Manual Form Perception Test adapted from Ayres (1972; 1980; 1989). Across the remaining studies outcome measures lacked definition in terms of reported reliability, validity, standardisation or available normative data such as ‘plastic spheres 5mm in diameter’ (Gori et al, 2012) , ‘9 objects differing in mass and volume’ (Kloos & Amazeen, 2002) and ‘haptic matching task’ (Fitzpatrick & Flynn, 2010).

Nine of the 10 studies examining haptic ability reported a positive association with age and three studies reported statistical significance. Fitzpatrick and Flynn (2010) reported significant improvements in haptic perception; 4 and 5 year olds demonstrated more accuracy than 3 year olds ($p = .007$) for the haptic matching task. Kalagher and Jones (2011a) reported a statistically significant effect of age ($p < .01$) for children matching novel category exemplars. Older children (5 years) made more shape based matches than younger children (2.5 - 4.5 years) in the haptic exploration condition. Children younger than 5 years matched “randomly” and did not produce efficient exploratory procedures when manipulating objects. In a subsequent study Kalagher and Jones (2011b) reported that young children (3 - 5 years) did in fact produce similar haptic exploratory procedures as adults when determining object properties. Kalagher and Jones (2011b) attributed the contrast in their findings to differences in testing procedures. Their first study required intermodal transfer (haptic to visual matching) and their subsequent study did not. The second study also added perceptual goals where children were asked to find information about specific object properties. Dunn et al. (2015) reported improvements in haptic object recognition accuracy from 3 - 12 years and the use of systematic exploration strategies accounted for most of the improvements in performance. Results showed that

capacity to extract object properties and accurately identify objects through haptic exploration improved however performance did not progress linearly as age increased.

Ardila et al. (2011) reported an association between increasing age and object identification performance on the Sensory Perception subtest. Lowest scores were reported for 5 to 6 year olds (13.8 - 14.9) when compared to 11 to 16 year olds (15.7 - 15.8) however the difference did not reach statistical significance. Ballesteros et al. (2005) reported that the ability to name objects, increased with age, however this progression was not linear across all age groups, although older children (14 - <16 years) performed better than younger children (3 - <5 years). Kloos and Amazeen (2002) reported that 5 year olds were more consistently proficient in detecting changes in mass of an object than 3 year olds. The interaction of mass, but not volume, and age was significant ($p < .005$). For haptic judgments of size without vision, Gori et al. (2012) revealed more errors in perceived size for younger children (6 - 10 years) than older children (13 - 16 years) and only older children showed a capacity for multisensory integration between visual size perception and haptic calibration. Van Grunsven et al. (2003) showed clear developmental changes across two age groups of increasing haptic gnostic hand function with 48% of the 6 year olds correctly drawing the objects that fingers of both left and right hands had perceived, and 91% and 61% of the 11 year olds drawing correctly objects perceived by the right and left hands, respectively. In contrast, Abu-Dahab et al. (2013) was the only study to report no significant effect of age for stereognosis between the youngest and oldest age groups 24% Errors (5 - < 8 years); 25% Errors (8 - < 12 years).

Discussion

Somatosensation matures through childhood into adolescence however, the present review found the pattern of somatosensory development varied depending on the outcome measure used and the aspect of somatosensation being measured, making it difficult to describe expected performance. Almost all of the studies examining touch reported a positive correlation between increasing age and tactile registration and tactile perception. These findings support current evidence of improvements in tactile registration and perception between childhood and adulthood (Lundy-Ekman, 2002). In comparison, Bleyenheuft et al. (2006) and Peters and Goldreich (2013) used a similar outcome measure (Grating Orientation Task) and reported contrasting results, however the authors did agree that age alone does not determine tactile spatial acuity and resolution. Both authors suggested that skin hydration, receptor density or central maturation play a role as previous studies have highlighted (Stevens & Choo, 1996; Manning & Tremblay, 2006). The effects of age on touch were dependent on the outcome measure and the aspect of touch measured. Understanding the impact of touch on hand function requires measurement of multiple aspects of the tactile construct. Comprehensive tactile assessment should include both phases of tactile registration and perception, a tactile assessment framework described by Auld et al. (2011; 2012).

A significant improvement in proprioceptive ability was seen between 5 to 8 years and mature patterns of coordination were not well developed until after 9 to 10 years of age (Contreras-Vidal, 2006; Goble et al., 2005; Hay et al., 2005). Recent literature also states that refinements in

proprioceptive input needed for motor output gradually occur throughout childhood from 6 years of age and continue well into adolescence (Mallau et al., 2010; Visser & Geuze, 2000). Goble et al. (2005) considered the impact of recalibration of internal body schemas in response to pubertal growth between the ages of 11 to 15 years (females) and 13 to 17 years (males). Similarly, Viel et al. (2009) suggested that body scheme disturbances may lead to a transient period of proprioceptive neglect for adolescents aged 14 to 15 years. These findings may indicate a diversion from proprioceptive feedback in preference for more stable sensory systems, such as vision, in order to smoothly coordinate movement at this age (Viel et al., 2009). Again, proprioceptive improvements are not linear or symmetric when considering the effect of age, with mixed results and variability seen between different testing conditions (Hay et al., 2005). Objective and repeatable measures are required to quantify changes in proprioception across all ages.

All studies examining haptic ability reported an increase in haptic performance and/or use of haptic exploratory procedures with increasing age. Four of the studies reported variation at an individual level, indicating that improvements did not progress linearly as age increased, however, it was possible to identify trends in means when considering group data (Abu-Dahab et al., 2013; Ballesteros et al., 2005; Fitzpatrick & Flynn, 2010; Kloos & Amazeen, 2002). Kalagher and Jones (2011a; 2011b) reported a presence of haptic exploratory procedures similar to adults by age 5, however current literature suggests that a child's ability to select the most efficient haptic exploratory procedure may develop at a later age (>7 years) (Alexander et al., 2002). Perceptual processing of haptic input, haptic-to-visual intermodal transfer and attentional capacity has been suggested as the

means of improving haptic perception across childhood to adolescence and why children may develop manual perceptual proficiency at very different rates (Cote, 2014; Fitzpatrick & Flynn, 2010; Kalagher & Jones, 2011a). Gender, prior knowledge of test objects and ability to select efficient exploratory procedures also affects performance on haptic test batteries (Alexander et al., 2002; Kalagher and Jones 2011a; 2011b).

While it is recognised that many factors influence the assessment of individuals in the developmental period, posing many challenges, amalgamating findings from this research is further complicated by the wide variability of methods and outcomes measures used (Dijkers et al., 2012). In the same way, developing, and evaluating the effectiveness of new interventions or other procedures becomes difficult without assessment tools standardised in the clinical populations for whom they are intended (Fess, 2002; Randall, 2008). Although measures of somatosensation impairment are used in research, few are normed, have robust psychometric properties, or demonstrated validity or reliability in children and adolescents (Connell & Tyson, 2012; Fess, 2002; Novak et al., 1993; Tassler & Dellon, 1995). Across the majority of included studies there was an absence of best practice methodology. Many assessment tools were designed specifically for research purposes and may have limited utility in clinical practice (Dijkers et al., 2012; Whyte et al., 2009).

Our ability to understand somatosensation in typically developing children, and best practice measures for clinical populations, is clearly linked to valid and reliable assessment (Cooper et al., 1995). In a recent clinimetric review by Auld et al. (2011) the current best practice measures of touch

for children with neurological disorders, such as cerebral palsy, were Semmes-Weinstein monofilaments, both static and moving two-point discrimination, and single-point localization (Weinstein, 1993; Tassler & Dellon, 1995; Burns, 1992). Best practice measures of limb position sense and kinesthesia for children is replication of therapist imposed movements of the upper limb without vision (Bentzel, 2008). Auld et al. (2011) suggests the best practice measure for haptic recognition for children with CP is the Klingels' stereognosis method requiring the use of 12 common objects, three matched pairs of similar items and six unmatched different items. Haptic test objects need to be easily manipulated by small hands and novel enough to avoid a ceiling effect (Auld et al., 2012). While the current review recognises best practices measures in CP, overall they lack psychometric rigour, similar to the outcome measures utilised in selected studies. Outcome measures in the current review showed face validity but were inconsistent in terms of overall rigor, reliability, or other types of validity, standard procedures or normative data. Further, varied units of measurement precluded any formal meta-analysis. Due to the lack of studies containing standardised measures and small sample sizes within the available evidence, interpretation of findings requires caution.

Somatosensation (touch, proprioception and haptic ability) increases with age from 2.5 years to 18 years however improvements do not progress linearly across time. The current review aimed to describe typical performance to use as a point of reference for children at risk of somatosensory impairment. Instead what we found were patterns of somatosensory development that varied depending on the outcome measure used and, hence, the aspect of somatosensation being measured, making it difficult to describe expected performance. Identifying and describing somatosensory deficits is crucial

in understanding the impact of impairment on hand function and to inform evidence-based frameworks for intervention. Children and adolescents with neurological conditions, such as cerebral palsy, would benefit from individual somatosensory profiles gained from comprehensive measurement tools that comprise touch registration and perception, proprioception and haptic ability.

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Figure 1. Flowchart of study selection

Author Manuscript

Table 1. Description of 4 studies excluded for methodological reasons

Author Manuscript

First author, year of publication, sample origin	Somatosensory modality of interest	Design and sample	Typically developing criteria	Outcome measure	Exclusion criteria
Alexander (2002) USA	Haptic perception	Cross-sectional N=35 (n=1 dropout) Aged 4-9 years 31 males 4 females	None disclosed	Cross comparison task (identical or not), haptically explored pairs of familiar (dinosaur) and unfamiliar (sea creature) models.	Measurement of outcomes not resistant to bias: Confounding factor; there was some association between age (and IQ) and knowledge, and the fact that children did better on cross comparisons of dinosaurs than of sea creatures suggests that knowledge is exerting some effect.
Auld (2012)	Tactile registration and tactile perception	Cross-sectional N=31 Aged 5-17 years 15 males 16 females	Typically developing children; no impairment in intellect (<70 on the Kaufman brief Intelligence test), upper limb performance (Jebsen), behavior (DSM-IV), or peripheral nerve lesions, upper limb fractures, or uncorrected visual impairment	Tactile registration: 20 item SWM kit. Spatial tactile perception: Single point localization; largest SWM. Two-point discrimination: Disk-Criminator; Double simultaneous, two bristles on a wooden rod. Texture tactile perception: AsTex. Motor enhanced tactile perception; stereognosis using 9 common objects.	Group not appropriate for objectives: Author unable to provide additional information for age comparisons due to small group sample size.
Bremner (2008)	Tactile spatial localisation	Cross-sectional Experiment 1 N=12 Aged 10 months 9 males 3 females N= 24 Aged 6.5 months 11 males 13 females	Gestational age exceeding 37 weeks	Direction of ocular and/or manual responses to vibrostimulation (10m group) to + or – vibrostimulation (6.5m group).	Measurement of outcomes not resistant to bias: Due to evidence of habituation across trials the outcome measure may be unreliable and the experimental method differs between the 2 groups being compared.
Liutsko (2014)	Proprioception	Cross-sectional	Self-described healthy, none	Computerized test and	Group not appropriate for

		N=41 Aged 12-17 years	receiving medication or had neurological problems. Normal or corrected-to-normal vision	equipment comprised a tactile screen and a sensory stylus (for hand drawing) to measure line length accuracy.	objectives: Author unable to provide additional information for age comparisons due to small group sample size
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Table 2. Description of included studies

First author, year of publication, sample origin	Somatosensory modality of interest and subcategory	Outcome measure	Design and sample	Typically developing criteria	Results	Methodological quality (Total sum/total possible sum)
Touch						
Riquelme (2011) Spain	Tactile registration Touch sensitivity	von Frey monofilaments.	Cross-sectional N=100 Aged 6-17 years 50 6-10yr olds 50 11-17yr olds	Cognitive level that allowed understanding of simple dichotomous questions.	Improved with age. There was an effect of age for touch sensitivity between age groups; touch thresholds in 6 - 10 years olds were greater (less sensitive) than adolescents (11 - 17 years).	Adequate (12/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to bias: No psychometric data reported.
Abu-Dahab (2013) USA	Tactile perception Finger recognition	Reitan-Kolve tests of Finger Agnosia.	Cross-sectional N=38 Aged 5-12 years 12 5-<8yr olds 26 8-<12yr olds	Healthy volunteers, no history of learning disability, neuropsychiatric disorder, psychological disorder, family history of autism	Improved with age. There was an effect of age with errors in finger recognition decreasing from 80% (5 - <8 years) to 44% (8 - <12 years).	Adequate (11/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to

				or heritable neuropsychiatric disorder.		bias: No psychometric data reported.
Dunn (2015) USA, Australia	Tactile perception Tactile discrimination	Tactile Discrimination Test using standard texture gratings for stimuli.	Cross-sectional N=71 Aged 3-12 years 29 3-6yr olds 42 7-12yr olds 35 males 36 females	Community-dwelling children, able to follow instructions.	Improved with age. Tactile discrimination improved with age with lowest scores reported in the youngest age group (3-6 years).	Strong (17/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to bias: Psychometric data reported.
Dunn (2013) USA, Australia	Tactile perception Tactile discrimination	Tactile Discrimination Test.	Cross-sectional N=64 Aged 3-<19 years 18 3-<7yr olds 46 7-<19yr olds	Community-dwelling children.	Improved with age. Tactile discrimination improved with age. A statistically significant difference ($p < .0001$) was reported between 3 - <7 year olds and 7 - <19 year olds.	Strong (17/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to bias: Psychometric data reported.
Bleyenheuft (2006) Belgium	Tactile perception Tactile spatial resolution	Grating Orientation Task (GOT) using an enlarged set of JVP domes.	Cross-sectional N=222 Aged 6-16 years 105 males 117 females	Free from disease or injury that could affect manual tactile sensitivity.	Improved with age. There was a statistically significant difference ($p < 0.001$) between 6 - 9 year olds and 10 - 16 year olds for tactile spatial resolution. Scores decreased (improved) with age until 10-11 years of age and then stabilised.	Adequate (14/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to bias: No psychometric data reported for children.
Bleyenheuft (2010) Belgium	Tactile perception Tactile spatial resolution	Grating Orientation Task (GOT) using an enlarged set of JVP domes.	Cross-sectional N=104 Aged 4-17 years 52 males 52 females	'Healthy', no hand disease or injury.	Improved with age. Tactile spatial resolution improved with age. There was a statistically significant difference in calculated GOT values; scores decreased (improved) with age from 4 - 17 years ($p < 0.001$) and stabilised at 10 - 16	Good (15/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to bias: No psychometric data reported for children.

					years. Lowest tactile spatial resolution was reported for the youngest children (4-5 years).	
Peters (2013) Canada	Tactile perception Tactile spatial acuity	Grating orientation task (GOT).	Cross-sectional N=100 Aged 6-16 years 50 males 50 females	Participants free from cuts, calluses or scars on their dominant index finger, as well as conditions that might affect their sense of touch such as diabetes, cognitive impairment, dyslexia or neurological conditions.	Didn't improve with age. No significant effect of age on tactile spatial acuity ($p = 0.403$). Age alone does not impact tactile spatial acuity; other factors may include fingertip size.	Good (16/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to bias: No psychometric data reported.
Yoshioka (2013) USA	Tactile perception Tactile localisation	Stimuli delivered via a 30-g probe with round rubber tip 7mm in diameter. Error was calculated as the distance between the stimulus and response location.	Cross-sectional N=50 Aged 4-9 years 18 4 yr olds 16 6 yr olds 16 9 yr olds	Normally developing children.	Improved with age. Mean errors in tactile localisation decreased with age from 4 to 9 years and was stable thereafter. The average error of stimulus-localisation was largest for children aged 4 - 6 years.	Good (15/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to bias: No psychometric data reported.
Proprioception						
Contreras-Vidal (2006) USA	Proprioception Kinesthesia, hand localisation	A kinesthetic-to-visual matching task void of visual feedback to assess hand localisation (internal hand representation) and control of movement. Movement time (MT), terminal end-point error (EPE) and initial	Cross-sectional N=15 Aged 5-10 years 5 5-6yr olds 5 7-8yr olds 5 9-10yr olds	None disclosed.	Improved with age. Statistically significant effect of age for all dependent variables (MT $p < .005$; EPE $p < .001$; IDE $p < .05$). Constant & variable errors decreased as age increased. End-point error variability of	Good (15/20) Comparison group was appropriate for objectives, however small sample size and subject group was not adequately described. Measurement of outcomes resistant to

		directional error (IDE) was measured.			the hand was largest for the youngest children and did not differ within the older age groups.	bias: No psychometric data reported.
Dunn (2013) USA, Australia	Proprioception Kinesthesia	Brief Kinesthesia Test asking participants to reproduce upper limb movements without vision after being guided by an examiner.	Cross-sectional N=100 Aged 3-<19 years 37 3-<7yr olds 63 7-<19yr olds	Community-dwelling children.	Improved with age. Kinesthesia improved with age with statistically significant differences seen between the younger (3- <7) and older age groups (7- < 19) ($p = 0.000$).	Strong (17/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to bias: Psychometric data reported.
Goble (2005) USA	Proprioception Proprioceptive accuracy	An active matching task of target positions void of visual feedback to assess proprioceptively guided movements.	Cross-sectional N=18 Aged 8-18 years 9 8-10yr olds 9 16-18yr olds	Good general health & able to perform common upper limb activities.	Improved with age. Statistically significant effect of age for accuracy in matching movements ($p < 0.001$). Matching error decreased as age increased.	Good (15/20) Comparison group was appropriate for objectives, however small sample size. Measurement of outcomes resistant to bias: No psychometric data reported.
Hay (2005) France	Proprioception Proprioceptive information	A tendon vibration technique and serial pointing task to assess the role of proprioceptive inputs for goal-directed movements. Constant error (CE), variable error (VE) and position error (PE) were measured.	Cross-sectional N=52 Aged 5-11 years	Average in terms of school achievement with no known sensorimotor impairments in their health records.	Improved with age. Statistically significant effect of age for CE ($p < .02$), VE ($p < .01$) & PE ($p < .02$). Variable & position errors decreased with increasing age with the lowest accuracy at age 5.	Good (15/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to bias: No psychometric data reported.
Dunn (2015) USA, Australia	Proprioception Kinesthesia, wrist position sense	A battery of 3 proprioceptive tests to assess wrist position sense and kinesthesia. (Brief Kinesthesia Test, Wrist Position Sense Test & Clinical Test of Wrist	Cross-sectional N=71 Aged 3-12 years 29 3-6yr olds 42 7-12yr olds 35 males 36 females	Community-dwelling children, able to follow instructions.	Improved with age. Kinesthesia and wrist position sense improved with age with a decrease in error reported from 3 to 12 years.	Strong (17/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to bias: Psychometric data reported.

		Position).				
Haptic ability						
Gori (2012) Italy	Haptic ability Haptic size perception	Participants were presented a sequence of differently sized plastic spheres in the hand (vision occluded) and were asked to report which sphere appeared larger.	Cross-sectional N=34 Aged 6-16 years 9 6yr olds 9 8yr olds 8 10yr olds 4 14yr olds 4 16yr olds	Children from elementary, intermediate and high schools in Prato (PO Italy).	Improved with age. More errors in perceived size for younger children (6 - 10 years) than older children (13 - 16 years).	Adequate (14/20) Comparison group was appropriate for objectives, however small numbers for 14-16yr olds. Measurement of outcomes resistant to bias: No psychometric data reported.
Kalagher (2011a) USA	Haptic ability Haptic perception, haptic exploration, haptic object recognition	Haptic exploration condition using 16 novel & 9 familiar objects to assess haptic-to-visual object matching skills.	Cross-sectional N=72 Aged 2.5-5 years 12 2.5yr olds 12 3yr olds 12 3.5yr olds 12 4yr olds 12 4.5yr olds 12 5 yr olds 5-7 males and 5-7 females in each age group	Representative of local community in ethnicity, racial identity & social class.	Improved with age. Statistically significant effect of age ($p < .01$). Older children (5 years) made more correct shape based matches than younger children (2.5 - 4.5 years). Children younger than 5 years matched "randomly" and did not produce efficient exploratory procedures when manipulating objects.	Strong (17/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to bias: No psychometric data reported.
Kalagher (2011b) USA	Haptic ability Haptic exploratory procedures	Haptic condition match-to-sample task, involving haptic inspection of 11 object sets to assess haptic exploratory behaviours.	Cross-sectional N=36 Aged 3-5 years 12 3yr olds 12 4 yr olds 12 5 yr olds	Representative of local community in ethnicity, racial identity & social class.	Improved with age. Children aged 3- 5 years can and do produce similar haptic exploratory procedures as adults when determining object	Strong (17/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to

			5-7 males and 5-7 females in each age group		properties.	bias: No psychometric data reported.
Kloos (2002) USA	Haptic ability Dynamic touch	A task involving identification of weight via the hand, void of visual feedback to assess perceptual ability through dynamic touch.	Cross-sectional N=18 Aged 3-5 years 7 3yr olds 5 4yr olds 6 5yr olds 11 males 7 females	None disclosed.	Improved with age. There was a statistically significant effect of age for detection of changes in mass $p < .005$. Children were more sensitive to changes in mass than younger children.	Adequate (12/20) Comparison group was appropriate for objectives, however small sample size and subject group was not adequately described. Measurement of outcomes resistant to bias: No psychometric data reported.
Abu-Dahab (2013) USA	Haptic ability Tactile perceptual skills (haptic object recognition)	Luria-Nebraska test of Stereognosis.	Cross-sectional N=38 Aged 5-12 years 12 5-<8yr olds 26 8-<12yr olds	Healthy volunteers, no history of learning disability, neuropsychiatric disorder, psychological disorder, family history of autism or heritable neuropsychiatric disorder.	Did not improve with age. Indicated no significant decrease in error for stereognosis between the youngest and oldest age groups 24% Error (5 - <8 years); 25% Error (8 - <12 years).	Adequate (11/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to bias: No psychometric data reported.
Ardila (2011) Mexico/Columbia	Haptic ability Tactile perception (haptic object recognition)	Child Neuropsychological Assessment to assess cognitive development (subtest included tactile object identification).	Cross-sectional N=788 Aged 5-16 years 350 males 438 females	No history of neurological, mental retardation, learning disabilities or psychiatric problems.	Improved with age. Performance in the tactile perception domain improved as age increased with the lowest scores reported for 5-6 year olds (13.8 - 14.9) when compared to 11-16 year olds (15.7 - 15.8)	Adequate (14/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to bias: Reference to psychometric data; high external validity.
Ballesteros (2005) Spain	Haptic ability Haptic perception	A haptic test battery to assess perceptual and cognitive abilities using active touch (20 subtests).	Cross-sectional N=60 Aged 3-16 years	Children with no known psychological or physical impairments.	Improved with age. Effect of age apparent, improvement in 'Object naming' subtest as age increased however no statistical significance. Older children (14 - <16	Good (15/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to bias: Psychometric data

					years) performed better than younger children (3 - <5 years).	reported; high internal consistency.
Dunn (2015) USA, Australia	Haptic ability Haptic object recognition	Brief Manual Form Perception Test.	Cross-sectional N=71 Aged 3-12 years 29 3-6yr olds 42 7-12yr olds 35 males 36 females	Community-dwelling children, able to follow instructions.	Improved with age. Children's haptic object recognition accuracy improved as they got older (from 3-12 years). Use of systematic exploration strategies accounted for most of the improvements in performance.	Strong (17/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to bias: Psychometric data reported.
Fitzpatrick (2010) USA	Haptic ability Haptic perception	Haptic matching task with 3-Dimensional shapes.	Cross-sectional N=40 Aged 3-5 years 12 3yr olds 15 4yr olds 13 5yr olds 25 males 20 females	None disclosed.	Improved with age. Age was statistically significant with 3 year olds having lower accuracy than 4 and 5 year olds ($p = .007$).	Adequate (14/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to bias: No psychometric data reported.
Van Grunsven (2003) The Netherlands	Haptic ability Manual haptic gnostic function	Investigation of a wooden object through passive touch without visual control to assess the development of gnostic hand function (shape and size detection).	Cross-sectional N=290 Aged 3-12 years 41 3-4yr olds 36 4-5yr olds 31 5-6yr olds 29 6-7yr olds 35 7-8yr olds 25 8-9yr olds 32 9-10yr olds 28 10-11yr olds 33 11-12yr olds	Healthy children selected from ordinary schools.	Improved with age. There is an effect of age on the development of morphognostic function; 48% of the 6 year olds correctly drew objects that their fingers had perceived compared to 61% - 91% for the 11 year olds.	Good (16/20) Comparison group was appropriate for objectives. Measurement of outcomes resistant to bias: Acceptable test-retest reliability reported.

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