World Journal of Otorhinolaryngology-Head and Neck Surgery (2018) 4, 57—66

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Review Article

Olfactory perception in children

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Received 6 February 2018; accepted 23 February 2018
Available online 21 March 2018

KEYWORDS
Development;
Olfaction;
Smell;
Odor identification;
Odor detection;
Pediatric Smell Wheel®;
Autism;
Odor discrimination;
Sex differences

Abstract The ability to smell is important for protection from danger and quality of life, even in children. Although smell loss is rare in children, it can be indicative of some childhood disorders and may be useful for understanding some disorders. This paper reviews the methods and results of behavioral testing olfaction in children, with an emphasis on odor identification, the most common method of assessing the sense of smell in both children and adults. The Pediatric Smell Wheel® is described as a relatively new and powerful tool for testing olfaction in children as young as 4 years of age. An example of its use in testing children with a childhood disorders (autism spectrum disorder, ASD) is provided in addition to a review of the literature on smell function in ASD. It is possible to reliably test sense of smell in children as young as 4 years old and many studies have shown that performance improves with age and can be impacted by childhood disorders. Sex differences in children are briefly discussed. Finally, the paper suggests other methods of testing olfaction in children, such as odor discrimination, that depend less on cognitive factors, which may enhance our understanding of the olfactory capabilities of young children.

Importance of olfaction in daily life

It is well established that the sense of smell is important for nutrition, safety, and quality of life. In one study of 445 persons presenting to a chemosensory disorders clinic, at least one hazardous event, such as food poisoning or failure to detect fire or leaking natural gas, was reported by 45.2% of those with anosmia, 34.1% of those with severe hyposmia, 32.8% of those with moderate hyposmia, and 24.2% of those with mild hyposmia, as compared to 19.0% of those with normal olfactory function.[1] In a longitudinal study of over a thousand non-demented older persons, mortality risk was 36% higher in those with low than with high scores on an odor identification test after adjusting for such variables as sex, age, and education.[2]

Although estimates of the prevalence of smell loss in the general population vary considerably,[3] there is consensus that, compared to adults, smell loss is relatively uncommon in children.[4] A recent analysis of over 1200 consecutive

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Peer review under responsibility of Chinese Medical Association.

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https://doi.org/10.1016/j.wjorl.2018.02.002
2095-8811/

patients presenting to the Smell & Taste Center at the University of Pennsylvania with chemosensory complaints revealed that children 16 and under-represented less than 2% of the patients. An earlier study of 750 patients reported that only 4% of that patient population had smell loss deriving from childhood.[5] That being said, children who are unable to smell are susceptible to the same hazards as adults. Moreover, olfactory testing can be useful in the early detection of such disorders as Kallmann's syndrome,[6] which, although quite rare (affecting 1/8000 males and 1/40,000 females[7]), can be treated if detected early. Furthermore, olfactory testing may prove useful in understanding aspects of some other medical conditions that children face, such as CHARGE[1],[8] obesity,[9] head trauma,[10,11] cleft palate,[12,13] and cancer.[14] Moreover, olfactory testing may shed light on neurodevelopmental disorders, including attention-deficit/hyperactivity disorder[15,16] and autism spectrum disorder[17] and as will be discussed below.

The negative effect of aging in adults on olfactory function is clear,[18,19] but less is known about olfactory function in child development, at least in part because there are special challenges in the testing of olfaction in children. For example, at the same time that changes in olfactory function may be occurring, children are developing cognitively—improving their memory, linguistic skills and attention span as well as expanding their experience of the world. Thus, tests of olfaction must take care not to conflate perceptual and cognitive development. Given these potential clinical applications, there is clearly a need for a standardized, reliable, and child-friendly test of olfactory function.

Objective methods of testing olfaction in children

There are several methods of assessing human olfactory function (for further details, see the Measurement of Chemosensory Function article in this volume). The two most common tests are *odor detection threshold* and *odor identification* tests, although numerous other tests are sometimes employed, including tests of *odor discrimination, odor memory*, and *assessments of suprathreshold intensity changes as a function of odorant concentration*. Stimuli (odorants) can be presented in one of several ways, including in opaque jars or squeeze bottles, in microencapsulated Scratch and Sniff® labels,[20] or in convenient wands or pen-like dispensers ("Snap & Sniff®" wands[21] and Sniffin' Sticks[22]).

Threshold Detection tasks typically use a "staircase" procedure (in which odor concentration is increased or decreased depending upon the participant's response on a previous trial) and determine the minimum concentration of an odor that can be detected. *Tests of Odor Identification* involve selecting a verbal label or picture associated with several (usually four) multiple choice response alternatives that best matches an odor. Odor identification is the most popular since it is reliable, practical, rapid and commercially available. Several tests of odor identification have been developed to test adults, including 40-, 12-, 8-, 4-, and 3-item versions of the University of Pennsylvania Smell Identification Test (UPSIT), a microencapsulated odorant test that presents odors in booklet form,[20] the "Sniffin' Sticks Test", a 16-item test that uses pen-like devices,[22] the 13-item Japanese "Odor Stick ID Test"[23] and the 16-item "Scandinavian Odor ID Test".[24]

Odor Discrimination involves, in its simplest form, the presentation of two stimuli in rapid succession and asking the participant to indicate whether the two stimuli are the same or different. A "triangle" version of this task involves presenting three stimuli and asking the participant to indicate which one differs from the other two. *Odor Memory* typically invokes recognition memory. A common paradigm is to have a participant smell and remember one or more odors and then to select, from a set of odors, the odor(s) that were previously smelled. Performance on tests of odor detection, discrimination, identification, and memory are highly correlated, suggesting that they measure the same underlying neural processes.[25]

Changes in olfactory performance in childhood

Odor detection threshold

While odor detection threshold measures do not require knowledge of the identity of odors, results from such tests have been variable, reflecting, in part, attention and reliability issues, as well as the influences of repeated testing. Moreover, many fewer studies have measured odor detection threshold (compared to odor identification) in children (Table 1). Toulouse and Vaschide[26] found that children between the ages of 3 and 12 improved in their ability to detect camphor as they aged. Dorries et al[27] found no consistent age-related pattern in odor thresholds for the unpleasant-smelling odorant pyridine for either boys or girls, although thresholds for the sweat-like odorant androstenone appeared to increase with age in males and decrease in females. While Koelega and Köster[28] found prepubescent children unable to detect two musk-like odorants (e.g., pentadecanolide or oxahexadecanolide) — odorants detectable by most adults — adult-like thresholds to the banana-like smelling amyl acetate were present. More recently, Monnery-Patris et al[29] found no decrease in thresholds with age across the age span of 4–12 years for the odor of R-(+)-Carvone (chewing gum), but did observe an age-related decrease in threshold for the odor of tetrahydrothiophene (a gasoline additive used in France). Some investigators have reported no differences in thresholds between children and young adults.[8,30–32] Solbu et al[33] have even found enhanced smell function in children relative to adults for trimethylamine (a fishy odor).

Odor identification

Odor identification, as measured using tests designed for adults, varies as a function of age-poorer performance is seen in both young children[34](Fig. 1) and in the elderly

[1] "CHARGE is an abbreviation for several of the features common in the disorder: coloboma, heart defects, atresia choanae (also known as choanal atresia), growth retardation, genital abnormalities, and ear abnormalities." https://ghr.nlm.nih.gov/condition/charge-syndrome.

Table 1 Results from studies that have explored odor detection thresholds in children.

Authors	*n*	Age (years)	Odors & method	Results	Sex difference
Cain et al, 1995[30]	125	8–14	1-Butanol; step procedure	Children had equal sensitivity to young adults	Not reported
Chalouhi et al, 2005[8]	25	6–13	Eugenol, aldehyde C14, PEA (rose); methods of ascending limits	Children had similar thresholds to adults	No
Dorries et al, 1989[27]	247	6–50	Pyridine and androstenone; method of constant stimuli	No age effect in odor thresholds for pyridine, thresholds for androstenone appeared to increase with age in males and decrease in females	Yes
Hummel et al, 2007[31]	146	3–12	PEA; staircase	No change in threshold across age	No
Koelega & Köster, 1974[28]	302 (approx. 50 per group)	Mean 9–20	Amyl acetate, pentadecanolide (exaltolide), oxahexadecanolide (Musk R-1)	Prepubescent children were on average unable to detect two musk-like odorants (e.g., pentadecanolide or oxahexadecanolide) but had adult-like thresholds for amyl acetate	Yes and no; odor dependent
Koelega, 1994[79]	228	9, 15 & 20	Amy acetate, n-butanol, iso-valeric acid, pentadecanolide, oxahexadecanolide; method of constant stimuli	No age effect for amyl acetate, but younger children had higher thresholds for the other odors	No (for children)
Lehrner et al, 1999[32]	137	4–90	1-Butanol; ascending staircase	Only a trend towards improved threshold with age. But youngest children were in one group (4–11 years)	Not reported
Monnery-Patris, et al, 2009[29]	152	4–12	R-(+)-carvone (chewing gum odor) and tetrahydrothiophene (gas additive); ascending limits	No effect of ages for gum. Age effect for tetrahydrothiophene	Yes (but due to verbal processing)
Solbu et al, 1990[33]	351	6–16; 20–42	Trimethylamine; ascending limits.	Bimodal distribution of thresholds for young and old; on average children performed better (if high sensitive group left in analysis); number of high sensitive people decreased with age	No
Toulouse & Vaschide, 1899[26]	163	3–5, 6 and 12	Camphor	Performance improved with age	Yes

(Fig. 4 in the Measurement of Chemosensory Function article of this volume). Many studies have replicated these findings (Table 2) and testing has occurred with children as young as 3 years of age. Performance improves from 50% to 60% correct (chance performance would be 25% for the 4-alternative forced-choice task) up to essentially adult performance in the later teenage years. Although all studies show this developmental trend, absolute performance varies as a function of odors employed in the task (Table 2). There is a clear odor dependence in odor identification — some odors are identified better than others.

It is worth noting that odor identification involves a level of cognitive and linguistic sophistication that is still developing in most toddlers and preschoolers. Many studies have demonstrated that testing of odor identification becomes possible at about age 3, suggesting that children's linguistic functioning is sufficiently mature at this age.[35] Very young children are still learning the relationship between names and the things to which they refer. Knowing that, for example, "dog" refers to the whole animal and not simply a part of it or another animal is challenging, even for concrete nouns.[36] The issue for odors is even more complex given that odor names refer to objects that emit odors, adding an additional layer of abstraction beyond labeling of visual objects. Children are more likely to refer to "count nouns" than to "mass nouns" and their reference to attributes of smell and taste are very rare and certainly are more rare than references to attributes such as size, color or location (see discussion in Engen & Engen[37]). Therefore, it would be a mistake to conclude that children's sense of smell is overall underdeveloped in their school-aged years. Particularly given that children's odor thresholds (at least for some odors) appear to be similar to adults', it is likely that developing the ability to identify odors involves experience with odors and the development of perception, cognition and language.

Most studies of odor identification in children have used tests designed to test adults. As pointed out by Laing et al[38] in 2008, at that time there was "no suitable clinical test" to measure olfactory function in children. Nonetheless, there are olfactory tests that have been administered to children,[38–42] and, as pointed out by Oozeer et al,[4] loss of smell

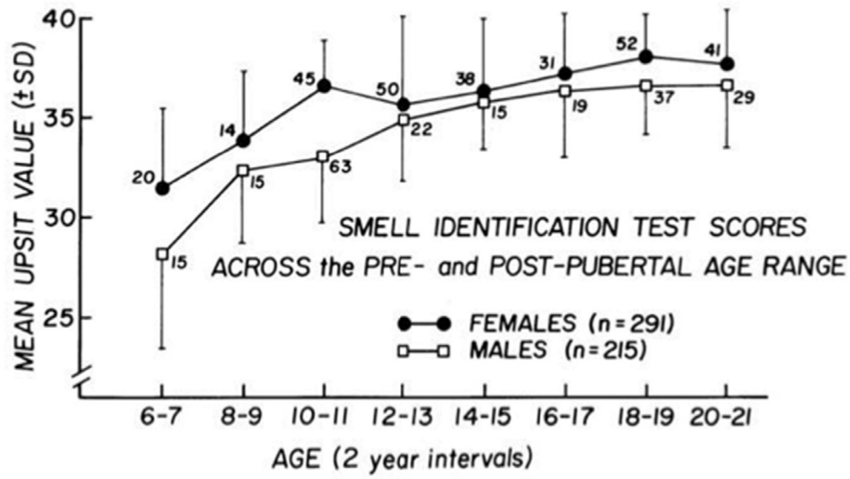

Fig. 1 Changes in scores on the University of Pennsylvania Smell Identification Test (UPSIT) across childhood and early adulthood years. From Doty (1986)[34] with permission. Copyright© 1986, Macmillan Publishing Company, a division of Macmillan, Inc.

function in children has "generated a large amount of scientific interest and research in the development of child-friendly screening olfactory tests"p. 513.

In response to this issue, three recent initiatives have developed odor identification tests with children in mind. Dalton and colleagues developed the National Institutes of Health Toolbox Pediatric Odor Identification Test that uses odors that are highly familiar to children (such as Play-Doh, chocolate, lemon, popcorn, and bubble gum) in a 4-alternative forced-choice test in either picture only[46] or picture and word format.[41] Schreiver et al[43] modified the adult Sniffin' Sticks by removing 2 of 16 odors to create a 14-item test for children. Cameron and Doty[44] introduced the Pediatric Smell Wheel® (PSW, Fig. 2) for the testing of children as young as 4 years of age. This game-like test assesses odor identification, providing children with both words and pictures to reflect the 4 possible responses (4-alternative, forced-choice task). The 11 odors in this test are well-known to children; namely, onion, soap, popcorn, bubble gum, banana, cherry, rose, chocolate, smoke, peppermint, and cinnamon. In our studies, children were found to enjoy the task and were able to complete the test in under 5 min. Children as young as 6 were able to self-administer the test.

Cameron and Doty[44] tested 152 children and youths between the ages of 4 and 19 with the PSW and found that their odor identification performance improved as a function of age. There was no difference between boys and girls (Fig. 3). As expected, college-aged participants performed significantly better than 4—5 year olds, 6—7 year olds and 10—11 year olds. Both 6—7 year olds and 10—11 year olds performed significantly better than 4—5 year olds, and 10—11 year olds scored higher than 6—7 year olds. The test scores of the 6—7 year-old group who self-administered the test did not differ from the test scores of the equivalent age group who were administered the test by an examiner.

As observed in other studies (Table 2), some odorants were more easily identified than others and performance across age groups depended on the odor. Performance significantly improved with age for all odors with the exception of bubble gum, which was well recognized even by the youngest children. Moreover, the test-retest reliability of the PSW, as measured by Spearman's, r was 0.70 and was statistically significant and consistent with the reliability of other tests of similar length, such as the Brief Smell Identification Test.[45]

The PSW could profitably be used in clinical populations in which differences in sensory processing are thought to exist. Although we have not specifically tested anosmic children, it is apparent that the PSW would detect children with no sense of smell in the same manner as observed for other forced-choice olfactory tests.[45] Data from five children were omitted from analysis in the Cameron & Doty' study[44] because they exhibited nasal stuffiness or their parents indicated that they had symptoms of a cold. Their PSW scores were very low (4 or fewer correct trials), demonstrating that the test is sensitive to smell loss. Moreover, the PSW may prove effective at evaluating smell function in children with development disorders, such as autism spectrum disorder (ASD), as described in the next section.

Olfaction and autism

Although questionnaire studies indicate that children with autism exhibit more "sensory symptoms", which may reflect either hypo- or hyper-sensitivity,[46,47] studies that have measured smell function (typically identification or detection) in either children, adolescents, or adults with ASD[2] are inconclusive. None have observed heightened odor identification performance in ASD; impairment has been noted in some and no impairment in others.

In the first study of adults with Asperger's syndrome, Suzuki et al[48] found impaired odor identification. In another adult study, Galle et al[49] found male adults with ASD scored lower on an odor identification task than male adults with Asperger's Syndrome (AS) and controls, who did not differ from each other.

In children and adolescents with ASD, some studies have found impairment on odor identification,[50,51] but others

[2] Note that the studies cited here were all conducted prior to the release of the DMS-IV, which does not distinguish between ASD and Asperger's Syndrome (AS).

Table 2 Results from studies that have explored odor identification in children.

Authors	n	Age (years)	Odor(s)	Results	Sex difference
Barber, 1997[80]	19,219 U.S. 3204 Africa	10–70	Androstenone	Small increase with age in U.S. sample; Youngest sample was not noticeably worse, but the age range was 10–19 years	Yes, but statistics not reported
Cain et al, 1995[30]	125	8–90	Baby powder, banana, bubble gum, butterscotch, coconut, chocolate, coffee, crayons, dirt(soil), disinfectant (Lysol), grape jelly, honey, onion, orange, peanut butter, perfume, potato chips, rubber, soap (ivory), and Vicks	Children performed worse (~50%) on unprompted identification (i.e., naming) task	Not reported
Chalouhi et al, 2005[8]	25	6–13	Citronella (lemon), cis-3-hexenol (grass), L-carvone (mint), 1-octene-3-ol (mushroom), vanillin (vanilla), and paracresyl acetate (horse dung)	Control group scored higher than children with CHARGE, but not differently than adults.	No
Cohen et al, 2014[14]	51	12+	Dettol™, sour, baby powder, fishy, grassy, paint, flowers, strawberry, cheesy, petrol, spicy, onion, Vicks VapoRub™, minty, orange and chocolate.	No smell loss and no significant correlation with age	Not reported
Dalton et al, 2009[35]	Pilot	3–17	Set 1: banana, lemon, Play-Doh, coffee, cinnamon and bubble gum Set 2: peanut butter, chocolate, flower, mint, Play-Doh and grape	Children as young as 3 could complete the task and performance increased with age (from 49% correct to 68% correct)	Not reported
Dalton et al, 2011[40]	369	3–17	Set 1: flower, lemon, Play-Doh, coffee, bubble gum, and peanut butter Set 2: flower, lemon, Play-Doh, coffee, bubble gum, and cinnamon	Children under 9 performed less well than adults, but depended upon the odor.	Not reported
Dalton et al, 2013[81]	1446 Also 2884	3–9 10–85	Match odor (5-item Toolbox test for children Play-Doh, chocolate, lemon, bubble gum and popcorn) scratch and sniff test to picture 10-item test, including cinnamon, coffee, smoke, natural gas and flower	Performance improved with age (from around 50% to nearly 85%) Children performed as well as young adults.	Not reported
DeWijk& Cain, 1994[82]	113	8–88 (Children 8–14)	Chocolate 1 and 2, dish detergent, tea leaves, burnt matches, mothballs 2, Vicks VapoRub™, unscented bleach, vinegar, mothballs 1, cinnamon, pipe tobacco, vanilla, scented bleach, soap, rubbing alcohol, disinfectant	Odor naming performance lower (32%) in children and the elderly (33%) than in younger adults (~50%) on 17 odors, but some odor dependence	Not reported
Doty et al, 1984[19]	1955	5–99	40-Item UPSIT	Lower performance in young and elderly on UPSIT	Yes
Doty, 1986[34]	509	6–21	40-Item UPSIT	Performance improved with age.	Yes
Dzåman et al, 2013[83]	91	3–10 Poland and Eastern Europe	Selected 6 of 21 items for their test (bubble gum, lemon, cola, mint, toffee, fish)	Improves with age, 96% correct on 4 of 6 odors. 3 year olds performed around 60% correct on 14 odors	No
Ferdenzi et al, 2008[62]	130	7–11	12 item Sniffin' sticks (included rose, leather, lemon, cloves, liquorice and coffee)	Improvement with age, independent of odor.	Yes
Forestell & Mennella, 2005[84]	296	3–8	Chocolate, coffee, bubble gum, strawberry, cola, cigarette, tuna and pyridine	Chocolate, 32% correctly identified; coffee, 27%; bubble gum, 24%; strawberry, 19%; cola, 11%; cigarette, 9%; tuna, 3%; pyridine, 1%)	Not reported

(*continued on next page*)

Table 2 (*continued*)

Authors	*n*	Age (years)	Odor(s)	Results	Sex difference
Frank et al, 2004[66]	116	4—35 USA	40-Item UPSIT	Children (4—9) performed worse (60%) than adults (85%).	Not reported
Hummel et al, 2007[31]	146	3—12 years	12 items; odors unspecified	Marginally significant effect of age; post hocs not significant with Bonferroni corrections	No
Hummel et al, 2011[85]	87	6—17, but none under 6 tested on odor ID	16 items; odors unspecified	6 year olds performed at about 60%, and 17 year olds at 87%	Yes, for combined tests.
Laing et al, 2008[38]	232	5—7 And 18—56	Floral, orange, strawberry, fish, chocolate, baby powder, paint, cut grass, sour, minty, onion, Vicks VapoRub™, spicy, Dettol™, cheese, and petrol	5, 6 and 7 year olds performed well (88—91% correct), but performed significantly worse than adults	No
Lehrner et al, 1999[32]	137	4—90	Unspecified which 10 of these 20 were targets: peppermint, aniseed, juice-fruit chewing gum, turpentine, cloves, cinnamon, cocoa, coffee, mustard, cigarette butts, lemon, orange, shower gel, brandy, almond oil, garlic, dried coconut, soap, gasoline, Nivea (skin cream)	4—11 year olds scored lower than young adults, equal to middle-aged adults and better than elderly adults	Not reported
Monnery-Patris et al, 2009[29]	152	4—12	Vanilla, lavender, domestic fuel, fish, violet, garlic, grass, orange, apple, lemon, anise, mint, eucalyptus, cinnamon, pentadecalactone (blackberry) and R-(+)-carvone (chewing gum)	Performance improved with age, with largest improvement between the youngest age groups	Yes, but explicable by verbal performance
Noll et al, 1990[86]	57	2.5—6	Apple, Play-Doh, popcorn, coffee, perfume, beer, whiskey, wine and cigarettes	Younger children (4 and under) performed less well than older children. Experience with alcohol odors (parental drinking) improved performance.	No
Oleszkiewicz et al, 2016[57]	76	10—14 & 15—18	Rose, leather, liquorice, clove, apple, fish — Cued and uncued	Main effect of age on the uncued task, but not the cued task, likely due to verbal fluency.	Yes, but partly explicable by verbal performance
Richman et al, 1992[39]	131	3.5—13	Baby powder, bubble gum, candy cane, fish and orange	Youngest performed at 66% correct; increase to 92% by 5 years.	Yes
Richman et al, 1995[41]	825	4—17	Baby powder, bubble gum, candy cane, licorice and peach	Performance improved up to 8 years in girls and 14 in boys.	Yes
Schriever et al, 2014[43]	537	6—17	Peppermint, banana, fish, orange, cinnamon, coffee, cloves, garlic pineapple, rose, lemon, liquorice, aniseed, shoe leather	Positive correlation between age and performance and significant difference between groups (6—8, 9—14, 15—17). Odor dependence.	No
Sorokowska et al, 2015[87]	1422	4—80	Peppermint, banana, fish, orange, cinnamon, coffee, cloves, garlic pineapple, rose, lemon, liquorice, aniseed, shoe leather, turpentine, apple	Lower performance in young and elderly.	No

Fig. 2 The Pediatric Smell Wheel® (PSW).[44] The PSW enjoys three advantages over most other published methods of testing children: (1) the odors were selected to be ones with which children are familiar; (2) both pictures and words are provided in the four-alternative forced choice task to reduce cognitive/linguistic load and potentially to improve performance; and (3) the test has a game-like quality that engages children. These qualities make the Smell Wheel a particularly attractive method of testing children's olfactory function and provide a testing format that appears to overcome attentional and other problems often associated with such testing. Photo courtesy of Sensonics International, Haddon Heights, NJ USA. Copyright© 2012 Sensonics International.

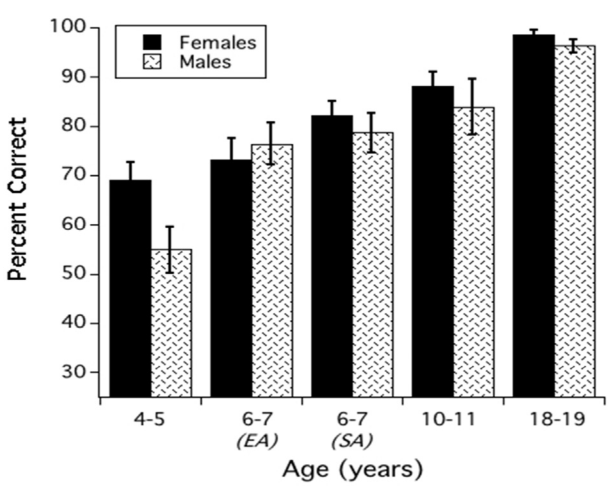

Fig. 3 Mean percent correct (±SEM) scores on the Pediatric Smell Wheel® as a function of age and gender.[44] EA = experimenter-administered; SA = self-administered.

have not.[52,53] Brewer et al[52] did, however, note an age-related decline in performance in their ASD study group. These authors suggested that perhaps that people with ASD "grow into deficit". More recently, May et al[54] tested this hypothesis with a longitudinal study of children with ASD and AS and found that the performance of control participants on the 40-item UPSIT when the 4 alternatives were presented as pictures, increased more than that of the ASD group.

In a pilot study using the PSW, Cameron and colleagues[55] tested 34 teenagers (17 with ASD, including AS and PDD-NOS (Pervasive Developmental Disorder — Not Otherwise Specified) and 17 typically developing controls) and reported that there was no difference in performance between the groups overall, nor on any particular odor (Fig. 4).

It is interesting to note that there is no evidence for improvement in odor identification in people with ASD, despite the self or caregiver reports of sensory sensitivities or abnormalities, including in their sense of smell, in this population.[47]

Sex differences

Cameron and Doty[44] reported no significant effect of gender on PSW test scores, although there was a trend towards females outperforming males. There are well established sex differences in olfaction, but they tend to be small, particularly for subjects under the age of 65 years (for a review see Doty & Cameron[56] and see Tables 1 and 2). Sex differences in performance on the PSW were expected given that some studies have reported sex differences in odor identification (Table 2). However, some of those studies demonstrated that the sex difference was associated with verbal fluency as opposed to odor perception[29,57] and the presence of pictures in the PSW along with words may have reduced the influence of language in this task. Moreover, performance on odor identification tasks is odor dependent in that some odors, particularly ones of biological significance, are identified better than others and there are reported sex differences in the sensitivity to specific

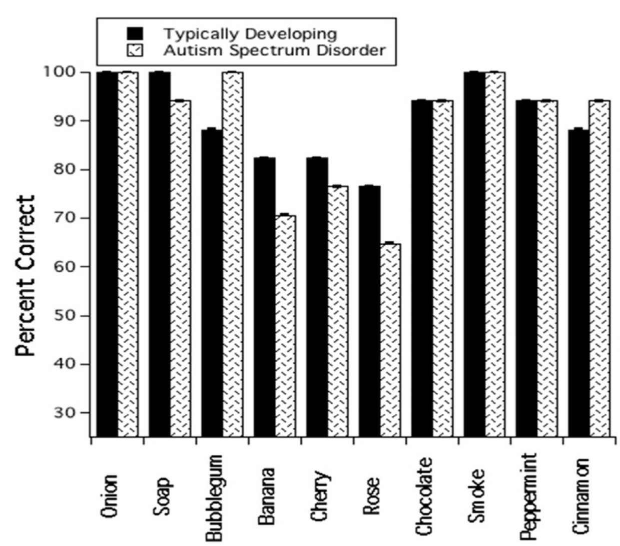

Fig. 4 Performance on the Pediatric Smell Wheel® for typically developing children and those with Autism Spectrum Disorder. The data represent mean (±SEM) percent of items correctly identified. Performance for both groups was around 80% correct and did not differ between groups on any individual odors.[55] Note: the popcorn smell was weak in the version of the test that we used and was thus excluded from the analysis.

odors in children (e.g., Dorries[27]; Koelega&Köster[28]). Most of the odorants used in this study have been shown not to exhibit sex differences[19] which, when present for other odorants, are usually small.[56]

There are several possible mechanisms for sex differences in olfaction. Among the most prominent and long-standing theory is that reproductive hormones underlie sex differences in olfaction.[56,58] Estrogen levels are positively correlated with olfactory sensitivity.[58,59] The logical prediction, therefore, would be that differences in olfactory perception should be present when reproductive hormones (particularly estrogen) start to emerge at puberty. The presence of sex differences in pre-pubescent children undermines that theory. A similar argument for heightened olfaction in pregnancy suffers a similar logical problem — though estrogen levels are thought to be related to enhance smell function in pregnancy, estrogen levels rise throughout pregnancy, but the changes in smell function, which have not been consistently found, are thought to be present early in pregnancy (for a review see Cameron[60]). It is likely that the relationship between reproductive hormones and olfactory sensitivity are not causally related in a simple fashion, but involve a more complex relationship between the olfactory system and a host of neuroendocrine factors.[56,60]

Other mechanisms to explain sex differences in olfactory function have also been proposed. For example, it has been suggested that some testing situations may improve the motivation of girls.[28] The sex of the experimenter can impact performance differentially for males and females[61] and the phase of the menstrual cycle[59] could provide an advantage for female participants. Experience and the relative importance of odor to girls and women have also been suggested to explain sex differences in olfactory perception.[62] However, female neonates more readily show a preference for the odor of their mother,[63] which suggests that there may be an innate or factors very early in development that underlie sex differences in olfaction.

Other measures of olfaction in children

This article has focused on odor identification and detection, but children have been tested using several other measures of olfaction. For example, there are a number of reports of children's performance on suprathreshold odor perception tasks, such as intensity judgments,[64] memory for odors,[32,65–69] recognition of peers and kin[70] and the development of odor hedonics and preferences.[71–75] Of particular interest is whether odor hedonics and preference for odors are hard-wired (as is largely true for taste) or develop with experience. This research question is still under investigation. Children have also been tested using questionnaires about smell[57,62] and with the Sniff Magnitude Test.[76]

Relatively few studies have examined children's performance on *odor discrimination tasks*. Richman and colleagues[41] developed a match-to-sample discrimination task with odors that were familiar to children. They tested 2–18-year olds and found that odor discrimination performance improved with age, but was only reliable starting at about age 5. Moreover, they reported that, compared to a test of odor identification, there was relatively less variability in performance. Richman and colleagues argued that the variability in performance on an identification task reflects non-olfactory variables, such as vocabulary, familiarity of odors and gender. Stevenson and colleagues[77] compared performance of children (6–11 years) and adults on a series of odor discrimination tasks and reported that children generally performed less well than adults. In one key experiment they used so-called "less familiar" odors and found that the ability of children to discriminate those odors was even worse than that of adults. Their results suggest that experience with odors improves discriminability.

The mechanisms underlying odor discrimination may be either perceptual or cognitive. However, it has been argued that odor discrimination is more likely to tap perceptual mechanisms, in part because it is less subject to the influence of non-olfactory factors.[47] Moreover, it has been suggested that the ability to discriminate odors may underlie children's ability to name and remember odors.[76] One potentially fruitful line of investigation would be to measure odor discrimination with uncommon odors,[78] which would reduce the influence of experience on performance. Clearly more research is needed and the results of studies on odor discrimination in development could help clarify what develops in olfaction in the childhood years.

Summary and conclusion

The ability to smell is important for quality of life and protection from danger, even in children. This review highlights the ability of children to perceive odors, primarily as tested with odor identification and detection tasks. Data from the administration of the recently-developed PSW was presented, demonstrating its usefulness in testing olfaction in children as young as 4 years of age. A review of studies examining smell function in children with ASD was provided, including novel findings from the application of the PSW. Our pilot data employing the PSW was consistent with the findings of others of no change in ability to identify odors in this population. Although there is evidence for sex differences in olfaction, the cause of such differences is not clear. Further work is needed to characterize the early sex differences and adjudicate between theories. Additionally, tests that are less influenced by cognitive demands, such as simple discrimination testing, may shed additional light on the olfactory capabilities of young children.

Acknowledgments

Thanks to Logen Bartz and Elizabeth Wenzel for assistance with the preparation of this manuscript and a special thanks to Richard Doty for feedback on previous versions of the manuscript.

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Edited by Yu-Xin Fang