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Spatial language difficulties reflect the structure of intact spatial representation: Evidence from high-functioning autism

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ABSTRACT

Previous studies have shown that the basic properties of the visual representation of space are reflected in spatial language. This close relationship between linguistic and non-linguistic spatial systems has been observed both in typical development and in some developmental disorders. Here we provide novel evidence for structural parallels along with a degree of autonomy between these two systems among individuals with Autism Spectrum Disorder, a developmental disorder with uneven cognitive and linguistic profiles. In four experiments, we investigated language and memory for locations organized around an axis-based reference system. Crucially, we also recorded participants' eye movements during the tasks in order to provide new insights into the online processes underlying spatial thinking. Twenty-three intellectually high-functioning individuals with autism (HFA) and 23 typically developing controls (TD), all native speakers of Norwegian matched on chronological age and cognitive abilities, participated in the studies. The results revealed a well-preserved axial reference system in HFA and weakness in the representation of direction within the axis, which was especially evident in spatial language. Performance on the non-linguistic tasks did not differ between HFA and control participants, and we observed clear structural parallels between spatial language and spatial representation in both groups. However, there were some subtle differences in the use of spatial language in HFA compared to TD, suggesting that despite the structural parallels, some aspects of spatial language in HFA deviated from the typical pattern. These findings provide novel insights into the prominence of the axial reference systems in non-linguistic spatial representations and spatial language, as well as the possibility that the two systems are, to some degree, autonomous.

1. Introduction

Representing space and talking about spatial relationships are fundamental abilities, necessary for understanding the world around us, successful wayfinding, tool use and everyday communication. Spatial representations emerge in the first months of life, when infants start to gradually acquire a basic understanding of spatial concepts like 'containment', 'support', 'above', 'below', and 'between' (Baillargeon & DeJong, 2017; Baillargeon, Li, Gertner, & Wu, 2010; Casasola, 2018). By age two, toddlers start to express these relationships in language, an ability that also advances gradually and follows a timeline that is strikingly consistent across languages (Johnston & Slobin, 1979; Johnston, 1988). For example, spatial terms such as *in/on*, *up/down*, and *here/there* appear very

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early in development, while projective terms like *front/behind* and *right/left* show a protracted learning trajectory and their usage is still not adult-like by age 6 (Clark, 1973b; Durkin, 1981; Harris, 1972; Kuczaj & Maratsos, 1975; Landau & Hoffman, 2005). Mastery of all these spatial terms requires a remarkable ability to express visuo-spatial information through language and thus, to map language onto non-linguistic representations. Theoretical and empirical studies have suggested that spatial language rests on a support of non-linguistic spatial representations (Clark, 1973a, 1973b; Hayward & Tarr, 1995; Landau & Hoffman, 2005; Landau & Jackendoff, 1993), enabled by sharing spatial properties across these two very different systems.

A key question about the nature of these shared properties is how close the correspondence between the two systems is, and how common structures are engaged within and across the two systems. Landau and Hoffman (2005) investigated these issues by looking at both linguistic and non-linguistic spatial abilities in people with Williams syndrome, a rare genetic disorder that gives rise to an uneven cognitive profile with relatively spared language but severely impaired spatial skills; they observed selective, parallel deficits in both domains. Here we focus on exploring these questions further by looking at a different developmental disorder that is also characterized by an uneven cognitive profile with ‘peaks’ and ‘troughs’ in both language and spatial cognition, but is not characterized by severe spatial impairment or intellectual disability. We examined spatial language and spatial memory in intellectually high-functioning individuals with autism (HFA) and typically developing controls (TD), all native speakers of Norwegian, focusing on behavioral outcomes as well as online processing of language and spatial memory. Specifically, we focused on representation of locations that were organized along the major (vertical and horizontal) axes of a reference system.

1.1. *The axial reference system*

One of the most fundamental properties of both linguistic and non-linguistic spatial representations is the reference system (Carlson-Radvansky & Irwin, 1993; Clark, 1973b; Landau & Jackendoff, 1993; Levinson, 1996; Tversky, 1996). Reference systems are an essential element in the mental representations of space that organize the position of a Figure object in relation to a Reference object. In the axial reference system, a set of three orthogonal axes (vertical, horizontal, and front/back axis) is centered on a Reference object or a location, which serves as the origin of the axes (see Fig. 1).

Consequently, when the set of axes is centered on the viewer (viewer-centered), one can represent the spatial relationship of a target (or Figure) object relative to himself or herself, e.g. “The chair to my left”, “The person on my right side”. Alternatively, if the set of axes is centered on an object or a landmark (object-centered), the relationship is represented relative to that object, e.g. “The ball is under the table”, “The building is in front of the City Hall”. The axes can also center on Earth (geocentric), allowing for the representation of spatial relationships in cardinal terms: north, south, east, or west. In addition to the origin and axes, another basic property in the axial reference system is direction within the axes, i.e. on which side of the Reference object the Figure sits (above or below on the vertical axis, left or right on the horizontal axis, and front or back on the front/back axis).

1.2. *Spatial language and spatial representation in the axial system*

The fact that certain aspects of the non-linguistic axial reference system so accurately capture the basic properties of spatial language has motivated the search for spatial primitives that might underlie both linguistic and non-linguistic representations of space. Such parallel representations would allow for relatively direct mappings between language and spatial representation and could also reveal constraints that are common to both systems. The candidate primitives that have been identified so far are the Figure and Reference objects, Axes, and Direction (Hayward & Tarr, 1995; Landau & Hoffman, 2005; Slack & Van Der Zee, 2003; Talmy, 1983). For example, in the sentence “a chair is *under* the table” (in Norwegian: “stolen er *under* bordet”), expression of location in the axial reference system in English (and also in Norwegian) includes noun phrases (NPs) encoding the Figure object

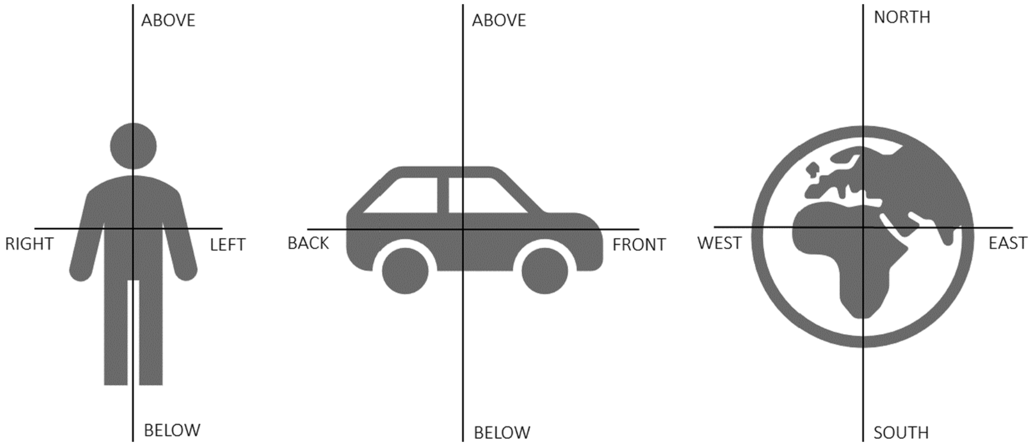

Fig. 1. Three examples of axial reference systems with a set of axes centered on the reference object: viewer-centered (left), object-centered (middle), and geocentric (right).

("chair"/"stol") and the Reference object ("table"/"bord"), and a preposition ("under") encoding the position of the Figure object on the vertical axis as well as the direction within that axis (Vertical Negative) relative to the Reference object. Hayward and Tarr (1995) developed an experimental task to examine whether there was indeed a one-to-one correspondence between the representations in linguistic and non-linguistic systems. Specifically, they wanted to determine the importance of axial structures in language and memory by closely matching linguistic and non-linguistic tasks. In order to do so, they used stimuli depicting a Reference object (a floating raft or a computer) and a Figure object (a bird, a fish, or a circle) in both language and memory tasks. In the language tasks, participants either produced or rated the acceptability of basic spatial terms (e.g. *above, below, left, right*) for different locations of the Figure relative to the Reference object. In the memory tasks, participants were asked to recall the position of the Figure object relative to the Reference or judge its position as the same or different in two pictures. Hayward and Tarr observed that the same locations that were remembered best also served as those for which people most frequently produced basic spatial terms. Additionally, these well-remembered and systematically named locations clustered along the axes centered on the Reference object, suggesting that the axes were critical in both memory and language (this effect was also validated cross-linguistically, see Munnich, Landau, & Dosher, 2001). In support of this, other studies have also shown that linguistic and non-linguistic spatial representations rely on a common axial structure (although with a different interpretation of this phenomenon, see Crawford, Regier, & Huttenlocher, 2000; Huttenlocher, Hedges, & Duncan, 1991).[1]

Remarkably, this organization has also been observed in individuals with Williams syndrome (WS), a relatively rare genetic disorder, despite the fact that these individuals exhibit broad and severe spatial impairments. Landau and Hoffman (2005) adapted the method used in the Hayward and Tarr's study to test WS individuals, who show relatively spared language but severely impaired spatial abilities (Bellugi, Lichtenberger, Jones, Lai, & St George, 2000; Bellugi, Marks, Bihrle, & Sabo, 1988; Bellugi, Wang, & Jernigan, 1994; Mervis & John, 2010). They observed the presence of axial organization (vertical and horizontal axes) in both language and spatial memory in this population. However, they also found deficits in the ability to assign direction within the axes, resulting in confusion of left/right directions within the horizontal axis, and above/below directions within the vertical axis. The results from the Williams syndrome studies show that directional coding within an axis might be generally more fragile and more prone to be compromised in the face of a developmental disorder characterized by spatial deficits. The fact that direction can be selectively impaired with preserved axial structure suggests that axis and direction components are dissociable and that this structural characteristic (presence of both axes and direction within axes) is common to both language and non-linguistic representations. Consequently, these findings suggest that there are certain sub-systems in spatial language and spatial cognition with distinct algorithms for solving different computational problems. But they also suggest that these sub-systems are similarly structured and constrained across the domains (Landau & Hoffman, 2007, 2012).

It is important to note that, despite a clear correspondence between spatial language and spatial representations in the examples above, the overlap between the two systems is only partial. While showing certain structural similarities (axes, directions), there are differences between the two systems, such as relatively fine-grained coding in the non-linguistic system (e.g. metric distance) but coarse coding in language (Kosslyn, Chabris, & Laeng, 2003; Landau & Jackendoff, 1993; Talmy, 1983). This suggests that aside from the overlap between the systems, there is also a certain degree of autonomy between these aspects of spatial language and the non-linguistic system that underlies it.

1.3. The relevance of high-functioning autism

Autism Spectrum Disorder (ASD) has often been conceptualized as the 'opposite' of WS (Rapin & Tuchman, 2008), with strengths in the visuospatial domain (Mitchell & Ropar, 2004; Stevenson & Gernsbacher, 2013) but impairments in social interaction and communication (American Psychiatric Association, 2013, DSM-5). In addition, ASD is viewed as quite different from WS in that individuals on the autism spectrum often show language delay or impairment. Although linguistic abilities are highly variable in ASD (Naigles, 2017; Tager-Flusberg, 2016; Tager-Flusberg, Paul, & Lord, 2013), language difficulties are still considered one of the main difficulties in ASD and remain the focus of a large body of current autism research (Barokova & Tager-Flusberg, 2018). The fact that people with ASD have difficulties in language but overall enhancement in visuospatial abilities raises the question of how they learn spatial language, especially whether their relative strength in non-linguistic visuospatial tasks might actually enhance their acquisition of spatial language.

Despite the overall asymmetry between linguistic and visuospatial abilities, it would be incorrect to treat the strengths and difficulties in ASD so categorically. Individuals with ASD are characterized by heterogenous cognitive and linguistic profiles that are punctuated by a range of selective deficits. Studies have shown that even intellectually high-functioning individuals with autism (HFA; typically defined as individuals with ASD and full scale IQ scores > 70; American Psychiatric Association, 2013) show selective deficits in a range of areas (Eigsti, de Marchena, Schuh, & Kelley, 2011; Howlin, 2003; Kamio, Robins, Kelley, Swainson, & Fein, 2007; Narzisi, Muratori, Calderoni, Fabbro, & Urgesi, 2013; Oliveras-Rentas, Kenworthy, Roberson, Martin, & Wallace, 2012; Vulchanova et al., 2013). For example, HFA individuals can have relatively large vocabularies but specific difficulties in the area of lexical processing (e.g. the use of idiosyncratic meanings and the absence of a shape bias in word learning, see Tek, Jaffery, Fein, &

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[1] More specifically, alternative accounts suggested that despite the presence of the axial structure in both linguistic and non-linguistic representations of space, the primary role of the axial structure was different in these two systems. That is, while cardinal axes served as the prototypes for linguistic spatial representations, the non-linguistic spatial representations were biased towards the diagonal angular locations, with cardinal axes serving as boundaries and not prototypical locations (Crawford et al., 2000; Huttenlocher et al., 1991).

Naigles, 2008; Tek & Naigles, 2017; Volden & Lord, 1991). Similarly, despite overall intact grammar, selective deficits have been observed in morphosyntactic processing in HFA (e.g. with the use of double complement constructions or personal and reflexive pronouns, see Eigsti, Bennetto, & Dadlani, 2007; Hobson, Lee, & Hobson, 2010; Janke & Perovic, 2015; Naigles et al., 2016; Paul et al., 2004; Perovic, Modyanova, & Wexler, 2013).

In the visual-spatial domain, many skills are intact or even enhanced in people with ASD, but a growing body of evidence points to a number of spatial deficits, including in high-functioning individuals. Specifically, HFA individuals show deficits in spatial working memory (Lai et al., 2017; Wang et al., 2017) and visual perspective taking (Pearson, Ropar, De, & Hamilton, 2013), but also with binding objects and locations (Ring, Gaigg, & Bowler, 2015), and spatial navigation (Lind, Bowler, & Raber, 2014; Lind, Williams, Raber, Peel, & Bowler, 2013; Ring, Gaigg, de Condappa, Wiener, & Bowler, 2018; Smith, 2015). These studies hint that specific aspects of spatial representation might be compromised in HFA and lead to difficulties in tasks such as memorizing spatial locations or perspective taking.

In sum, people on the autism spectrum show selective deficits in both language and cognition, leading to an overall uneven profile marked by ‘peaks’ and ‘troughs’. This suggests that even when the overall intellectual abilities are within the normal ranges, as in the case of HFA individuals, some aspects of knowledge can be compromised while others remain intact. As such, the HFA population is a good model for testing the hypothesis that linguistic and non-linguistic representations of space are yoked to one another. Specifically, it allows us to test whether selective deficits in one domain (language) align with deficits in the other domain (spatial representation). Even though selective deficits have been reported in spatial cognition in HFA and preliminary reports point to difficulties in spatial language in this population (Ohta, 1987; Perkins, Dobbinson, Boucher, Bol, & Bloom, 2006; Vulchanova et al., 2013; Vulchanova, Talcott, Vulchanov, & Stankova, 2012), no systematic comparison between spatial language and non-linguistic spatial abilities in autism has been conducted so far. Thus, it is unclear whether spatial language difficulties mirror corresponding deficits in spatial cognition or simply reflect an overall weakness in language in this population (Barokova & Tager-Flusberg, 2018).

The current study of HFA is a natural extension of previous work with WS. In the case of severe spatial deficits, as in WS, both linguistic and non-linguistic representations of space showed parallel deficits. The case of autism is less clear, because findings on language and space indicate some weaknesses in both, but there have not been any studies examining exactly the same spatial properties across the two domains. Doing so in our studies allows us to test whether any weakness in one area will be reflected in the other. Additionally, the lack of intellectual disability in the HFA population allows us to match the abilities of HFA individuals with chronological age-matched typically developing individuals and thus, provides a more direct comparison of the spatial abilities between the groups (Jarrold & Brock, 2004; Mervis & Klein-Tasman, 2004; Mervis & Robinson, 2003).

1.4. The current studies

In the current set of studies, we carry out a comparison of spatial language abilities and non-linguistic spatial representation in groups of HFA and typically developing (TD) individuals, examining their ability to represent the structure of the axial reference systems. As individuals with HFA display uneven profiles in both cognitive and linguistic domains with characteristic ‘peaks’ and ‘troughs’, we ask whether the fundamental axial reference system and spatial language that depends on this system show selective strengths and weaknesses within the spatial domain. We also ask whether selective difficulties (if there are any) within non-linguistic and linguistic spatial abilities are similar, i.e. corresponding patterns of performance occurring across the two systems.

Based on previous findings on the effects of Axis, Direction and Distance in typically developing children and adults, and in developmental disorders (Hayward & Tarr, 1995; Landau & Hoffman, 2005; Munnich et al., 2001), we formulated two main predictions. First, we predicted that there would be within-subject effects of Axis, Direction, and Distance. Specifically, we predicted to see the effects that cross language and memory, that is the effect of Axis (i.e. the linguistic and non-linguistic advantage for locations along the vertical and horizontal axes) and the effect of Direction (more fragile representation of direction, e.g. left vs right, compared to the representation of one axis, e.g. vertical, vs. the other, e.g. horizontal). We also predicted within-subject effects of Distance (i.e. decreasing accuracy with increasing distance of the Figure from the Reference object), but only in the non-linguistic task and not in the linguistic task. This is based on the assumption that non-linguistic representation of space includes metric information, but linguistic spatial terms are categorical.

Second, we formulated predictions about between-subject effects in language and memory. Specifically, we predicted no differences between HFA and TD groups in the representation of axial structure (Axis). If the representation of axial structure is resilient in the presence of other spatial deficits, it should also organize spatial language and memory in HFA. However, we predicted that Direction discrimination might show a weakness in language and memory in HFA compared to TD individuals based on previous evidence for poorer direction discrimination in young children and individuals with spatial deficits (Landau & Hoffman, 2005). Alternatively, if the representation of direction is intact in HFA, we predicted that we would see no differences between the groups. Note, however, that due to the complexity of the cognitive and linguistic profiles in HFA, a different pattern could also emerge (e.g. atypical deficits or deficits that do not align across spatial language and spatial cognition systems).

In order to test these predictions, we adapted the method from Landau and Hoffman (2005), based on the original idea by Hayward and Tarr (1995), to accommodate both children and young adults with and without HFA. Landau and Hoffman’s method was developed to investigate the parallels between spatial language and non-linguistic spatial representation in children. It consists of four short tasks: two that test non-linguistic representations of the axial reference systems and two tasks that test linguistic abilities that rely on the same reference system and depend on location along two primary axes and direction within each axis. All four tasks were used in the current study: (1) Non-linguistic spatial representation of axis and distance from the Reference object, (2) Non-linguistic spatial representation of direction within the axis, (3) Spatial language production, 4) Spatial language comprehension.

Because participants in the current samples were older compared to the sample from the Landau and Hoffman's study and they did not display a severe spatial impairment nor an intellectual disability, we increased the level of difficulty in the tasks. We did so by increasing the distances between the Figure object and the Reference object and decreasing the size of the Reference object, while maintaining the proportions from the original study. Note, however, that we maintained the original, small distances in the second (forced-choice) task because in this task, larger distances could in fact make it easier to discriminate between the locations.

Importantly, we introduced a new method to study the parallels between spatial language and spatial representation. Besides offline data, such as accuracy (reported in the original studies by Hayward and Tarr (1995) and Landau and Hoffman (2005)), we recorded participants' eye movements during the tasks to provide new insights into the online processes underlying spatial language and memory for spatial location. A large body of evidence has shown that where we direct our gaze is indicative of concurrent language or memory processing. Linguistic interpretations guide eye movements almost instantly to the relevant locations (Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995) and visual memory guides eye gaze, e.g. in visual search (Castelhano & Henderson, 2007). Crucially for the current study, eye gaze is directed towards spatially meaningful locations even when there is nothing to look at. For example, people move their eyes to regions on an empty screen that were previously occupied by objects that are being retrieved from memory (Hollingworth, 2005; Laeng, Bloem, D'Ascenzo, & Tommasi, 2014; Martarelli & Mast, 2013; Renkewitz & Jahn, 2012). Likewise, language can mediate eye movements by causing eye gaze to fixate on the regions of the empty screen that correspond to verbal instructions (Altmann, 2004; Johansson, Holsanova, & Holmqvist, 2006; Richardson & Spivey, 2000). Importantly, this effect is equally strong irrespective of whether the encoding is visual or linguistic (Johansson et al., 2006), and is present already early in development (at least from 6 months, see Richardson & Kirkham, 2004). Finally, eye gaze has been proven to be particularly informative when considering the processing of spatial terms, as spatial directions expressed in language can guide eye gaze to the relevant areas on the blank screen (Demarais, 1998; Spivey & Geng, 2001).

Thus, along with the final responses, we examined the moment-by-moment computations underlying spatial memory and spatial language processing that precede participants' answers in the tasks. We hypothesized that the online processes would reveal the weaknesses in spatial representation and language that might not be visible in the final outcome of these processes, i.e. participants' offline responses. For example, when retrieving spatial location from memory or linguistic descriptions, individuals can gaze at the correct (target) locations, but they can also look at the alternative (non-target) locations (Allopenna, Magnuson, & Tanenhaus, 1998). This gazing at non-target locations can serve as an indicator of lower efficiency or higher uncertainty in language and memory processing (Castelhano & Henderson, 2007; Henderson & Ferreira, 2004; Huettig, Olivers, & Hartsuiker, 2011; Huettig, Rommers, & Meyer, 2011; Krajbich & Rangel, 2011). Thus, we looked at the proportions of looks to non-target locations ('non-target fixations') to uncover potential weaknesses in spatial language and spatial memory processing in the current tasks. Finally, because arriving at the final response is a complex process that might involve rapid changes of mind (Resulaj, Kiani, Wolpert, & Shadlen, 2009), and gaze patterns are likely to reflect those changes, we also looked at the patterns of the initial eye fixations (Early Fixations) and final fixations before the response in the tasks (Late Fixations).

The studies were conducted in compliance with the Regional Committees for Medical and Health Research Ethics (REK) in Norway (reference number 2015/1642). The same participants participated in all four experiments. The total amount of time required to complete the experiments was about 30 min.

Testing took place in the Language Acquisition and Language Processing Lab at the Norwegian University of Science and Technology (Trondheim, Norway) and in the Cognitive Laboratories at the University of Oslo (Oslo, Norway). The same apparatus, software, and external devices were used in both testing locations. At the end of the testing procedure, all participants were allowed to choose a gift (board games, puzzles, bags, gift cards for cinema or a water park) as a compensation for their participation in the study.

2. Experiment 1: Spatial representation of axis and distance

The first experiment investigated memory for object location in the axial reference system. Specifically, we asked whether individuals in the HFA and TD groups would find it easier to recall the locations along the vertical and horizontal axis (OnAxis) compared to other locations (OffAxis). We predicted that we would observe the effects of Axis on participants' memory, i.e. higher accuracy and fewer non-target fixations, in OnAxis compared to OffAxis trials. In addition, as non-linguistic systems code fine-grained information like metrics, we also expected to see an effect of Distance on participants' memory, i.e. higher accuracy and fewer non-target fixations for locations closer to the Reference object compared to the locations further away.

2.1. Participants

Twenty-three high-functioning individuals with autism (HFA, 6 females, age range: 9–27, M = 17.8, SD = 6.2) and 23 typically developing individuals (TD, 9 females, age range 9–27, M = 18.0, SD = 5.2) participated in the study. The participants were recruited through the local schools and the national and local branches of the Autism Society in Norway (*Autismeforeningen i Norge*). Only individuals who had received a formal diagnosis of Autism Spectrum Disorder or Asperger Syndrome (according to the DSM-IV criteria) from an authorized psychologist in Norway and were native speakers of Norwegian were included in the HFA group. We included only participants that were high-functioning individuals without intellectual disability (i.e. Full Scale IQ scores higher than DSM-5 cut off point for intellectual disability set at about 70; American Psychiatric Association, 2013).

The groups were matched on chronological age and perceptual abilities (Perceptual Reasoning Index, Wechsler Intelligence Scales; Wechsler, 2003, 2008; Norwegian Standardization Editions: 2009, 2011 respectively; see Table 1). In addition, the groups

Table 1
Descriptive characteristics of the HFA and TD groups.

	Assessment	HFA (N = 23) M (SD)	TD (N = 23) M (SD)	p-value (independent samples *t*-tests)
Chronological Age		17.8 (6.2) range: 9–27	18.0 (5.2) range: 9–27	$p = .878$
Gender (M/F)		17/6	14/9	
Perceptual Reasoning	Perceptual Reasoning Index WISC-IV or WAIS-V	110.35 (16.932)	109.83 (14.070)	$p = .910$
Verbal Comprehension	Verbal Comprehension Index WISC-IV or WAIS-V	107.91 (13.688)	113.83 (9.528)	$p = .096$
Morphological Comprehension	Morphological Comprehension subtest score TOLD-I:4	35.57 (10.148)	39.35 (5.390)	$p = .124$
Autistic traits/Symptoms severity	AQ/CAST Questionnaire	0.56 (0.16)	0.15 (0.13)	$p < .001^{***}$

were compared on certain language abilities: general Verbal Comprehension (Wechsler Intelligence Scales) and Morphological Comprehension (TOLD-I:4; Hamill & Newcomer, 2008; Norwegian adaptation, see Vulchanova, Foyn, Nilsen, & Sigmundsson, 2014). The Morphological Comprehension subtest was chosen from the TOLD-I:4 test as the most comprehensive test of grammar (the examinee states whether a sentence is grammatically correct or incorrect) that at the same time did not put additional demands on working memory or require organizational language skills compared to the other subtests from the battery (the participant simply judges the sentence as grammatically correct or incorrect instead of combining sentences to one or rearranging words, see: Carmichael, Fraccaro, & Nordstokke, 2014). Participants under 16 years old completed the Wechsler Intelligence Scales for Children (WISC-IV) and participants over 16 years old completed the Wechsler Adult Intelligence Scales (WAIS-IV). All participants completed the Test of Language Development (TOLD-I:4). Wechsler Intelligence Scale tests were conducted independently in a separate testing session. Test of Language Development was conducted in the same testing session as the experiments (after two first experiments and before two last experiments). The total time required to complete the background tests was about 2.5 h.

In addition, we used The Autism Spectrum Quotient (AQ; Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001; Norwegian translation) and the parents of participants under 16 years old filled out The Childhood Asperger Syndrome Test (CAST; Scott, Baron-Cohen, Bolton, & Brayne, 2002; Norwegian translation) to screen for the presence or absence of autistic traits in the groups and to acquire an additional information about the symptoms' severity in the HFA group. The average proportions of total scores differed significantly between the groups (HFA: M = 0.56, SD = 0.16; TD: M = 0.15, SD = 0.12), with HFA individuals scoring reliably higher than the controls (see Table 1).

2.2. *Design and materials*

The design of the experiment included three within-subject factors: Axis (OnAxis, OffAxis), AxisType (Vertical, Horizontal) and Distance (Contact, 2 squares away, 4 squares away from the Reference object), as well as one between-subject factor, Group (HFA, TD). The dependent measures included offline (mouse clicks to relevant locations) and online responses (non-target eye fixations).

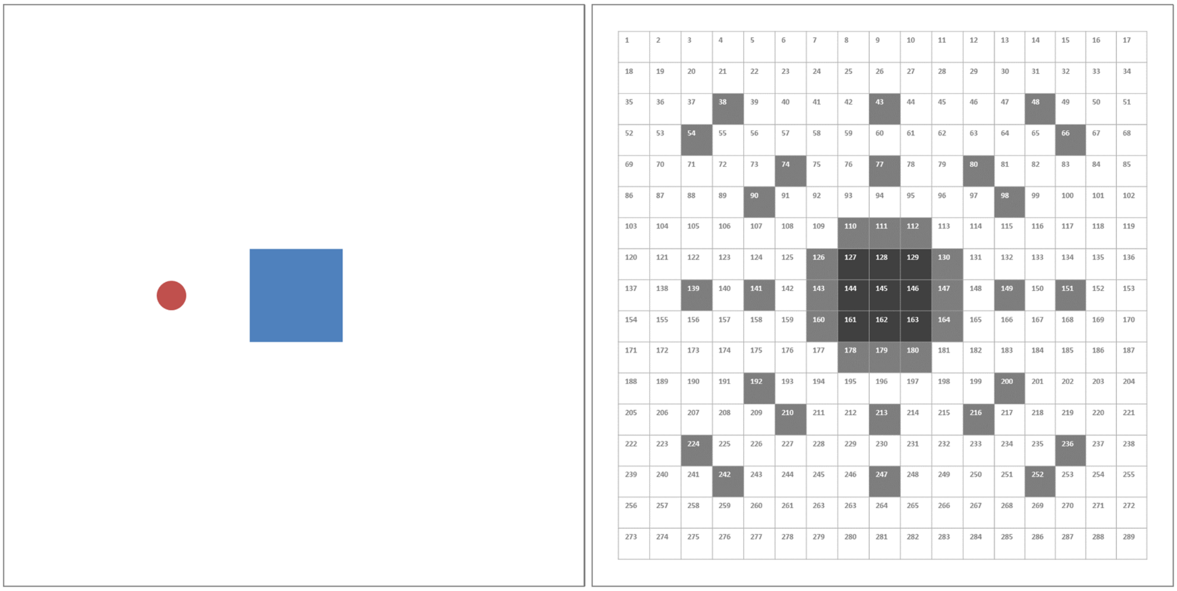
The stimuli consisted of a series of plain, two-dimensional images of a Reference object (a blue square) placed in the middle of the screen and a Figure object (a red circle) in one of the locations around the Reference object (see Fig. 2). The Reference object was in the middle of a 17 × 17 grid (not visible at any time to the participants), which was superimposed on the images. The Reference object's size and location corresponded to the 3 × 3 figure in the middle of the grid (see dark gray locations in Fig. 2). The size of all stimulus images was 1024 × 1024 pixels.

Out of all 280 regions around the Reference object, 36 regions were selected as target locations (see the squares in light grey in Fig. 2). These target locations corresponded to the 36 locations from Landau and Hoffman (2005) study and consisted of 8 locations along the axes of the Reference object (OnAxis), 12 locations in contact with the Reference object (Contact) and 16 locations diagonally to the Reference object (OffAxis). To accommodate older and intellectually high-functioning children as well as young adults, we increased the level of difficulty in the task, by increasing the distance of the target regions from the Reference object and decreasing the size of the Reference object itself. Consequently, 12 locations were in contact with the Reference object, 12 locations were 2 squares away and 12 locations were 4 squares away from the Reference object (compared to contact, 1 and 2 squares away in Landau and Hoffman's study).

2.3. *Procedures*

Participants (over 18 years old) or their parents (for participants under 18 years old) filled out and signed the consent form for the voluntary participation in the study. In cases where the parents and not the participants themselves gave written consent, a child assent was additionally obtained. All participants and their parents (if the participant was under 18 years old) were informed about the participation requirements, experimental procedures in the study, and the total amount of time required for completing all tests. Participants were given detailed instructions before the experiment.

The experimental stimuli were shown on a built-in screen of the Tobii T120 eye-tracker (Tobii Technology, Danderyd, Sweden; www.tobii.com) at a display resolution of 1280 × 1024. All stimuli were presented using E-Prime 2.0 software (Psychology Software



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68
69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85
86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102
103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119
120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136
137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153
154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170
171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187
188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204
205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221
222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238
239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255
256	257	258	259	260	261	263	263	264	265	266	267	268	269	270	271	272
273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289

Fig. 2. Examples of the materials used in the study: a stimulus from one of the memory tasks (left panel) and superimposed grid (not visible to the participants) with all 36 target locations (marked in light grey) tested relative to the reference object in the middle (right panel).

Tools Inc., Pittsburgh, USA; www.pstnet.com/products/e-primewww.pstnet.com/products/e-prime/). During the experiment, the eye movement were tracked together with the offline responses. The Tobii T120 eye-tracking system tracks participants' eye movements using infrared corneal and pupil reflection. In the T120 model used in the current study, the camera is built into the rim of a 17-in. TFT monitor and allows for a 300 × 220 × 700 mm freedom of head movements at a tracking distance of 50–80 cm. Participants were seated in a stable chair within that distance range from the monitor screen (about 60 cm). Eye gaze data were recorded at a stable sampling rate of 120 Hz throughout the study.

The participants were told that their task was to remember where the red circle was in relation to the blue square. Next, more detailed instructions appeared on the screen with the examples of what the stimuli might look like. The participants started a short practice session followed by a standard calibration procedure. If the calibration was successful, the main part of the experiment started. The main part consisted of 36, fully randomized trials. Each trial started with a fixation cross followed by an encoding phase (1000 ms) with an image of a red circle in one of the 36 target locations around the Reference object (see Fig. 2), a mask to prevent the afterimage effects on memory (500 ms), and a retrieval phase (see Fig. 3). The participant's task was to remember the circle's location during the encoding phase and to click with the mouse cursor on the exact location where the red circle was in the retrieval phase. When the response was given, the experimenter proceeded to the next trial. The participants were allowed to change their answer if they stated immediately after the response that they clicked on a wrong location. This practice was implemented in order to ensure that incorrect responses were not due to limitations resulting from difficulties navigating the mouse or general problems with motor control.

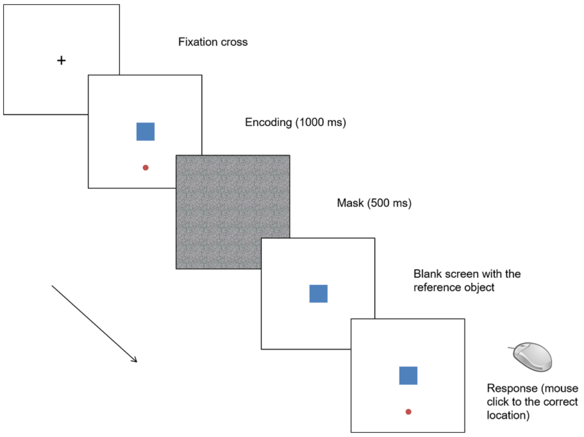


Fig. 3. The structure of the trial in Experiment 1: fixation cross, followed by an encoding phase, a mask and a retrieval phase with a response. Each of the 36 target locations was shown only once.

2.4. Results

The analysis was conducted in two main steps: we first examined the offline responses, investigating the effect of Axis and Distance on the accuracy rates. Secondly, we looked at the online measures, examining the effects of Axis and Distance on the proportions of non-target eye fixations, i.e. the proportions of eye fixations that were not directed to the target location during the retrieval phase (but occurred before the response).

Accuracy data. The proportions of correct responses were calculated separately for all 36 target locations around the Reference object. Fig. 4 shows the distribution of average accuracy scores per target location for HFA and TD group. We first investigated whether there was an advantage for locations OnAxis compared to locations OffAxis. Contact locations showed ceiling effects (99% accuracy), pointing to a clear advantage for retrieving locations adjacent to the Reference object, and were therefore excluded from this analysis.. We ran a 2 (Axis: OnAxis, OffAxis) × 2 (Distance: 2, 4 squares away from the Reference object) × 2 (Group: HFA, TD) analysis of variance on proportion of correct responses. Correct responses were collapsed across axis types, and because this constituted 4 locations per each Distance for OnAxis locations and 8 locations per Distance for OffAxis locations, these were converted into proportion correct. The analysis showed a main effect of Axis, $F(1, 45) = 7.29$, $p = .01$, $\eta^2 = 0.124$, with locations OnAxis retrieved more accurately (M = 0.83) than locations OffAxis (M = 0.77). We also observed a main effect of Distance, $F(1, 45) = 16.112$, $p < .001$, $\eta^2 = 0.267$, showing a memory advantage for locations closer to the Reference object (2 squares away; M = 0.83) compared to locations further away (4 squares away; M = 0.75). There was no difference in the accuracy rates between the HFA and TD group, $F(1, 45) = 0.402$, $p = .53$. There were no significant interactions (all $ps > 188$).

Next, we examined whether memory performance differed depending on the type of axis (Vertical, Horizontal). We calculated the average accuracy scores for the Horizontal vs. Vertical trials (collapsed over distances) for each participant and ran a 2 (AxisType: Vertical, Horizontal) × 2 (Group: HFA, TD) analysis of variance on the calculated scores. There was no effect of AxisType, $F(1, 45) = 0.835$, $p = .366$, $\eta^2 = 0.019$, nor an effect of the Group, $F(1, 45) = 0.264$, $p = .61$, $\eta^2 = 0.006$, nor interaction of AxisType × Group, $F(1, 45) = 0.003$, $p = .957$, $\eta^2 = 0.000$.[2]

Gaze data. We obtained eye fixations to all locations in the grid superimposed on the stimulus image. Fixations to the blue square in the middle were filtered out and excluded from the analysis, because looks to the Reference object should not count as fixations to an incorrect location. The remaining locations constituted 280 Areas of Interest (AOIs) around the Reference object. The fixations were categorized as "Hits", if they fell into the correct target AOI (the same as the circle's location in the preceding encoding image) or "Non-target fixations" if they fell into the incorrect AOI in a given trial. The gaze data from one participant were excluded due to technical difficulties during the calibration and the recording. We proceeded with the analysis on the gaze data from 45 remaining subjects.

In order to examine the temporal evolution of the retrieval processes, the non-target fixations were collapsed into two FixationType categories: Early Fixations (the first half of the time from retrieval onset to the participant's response) and Late Fixations

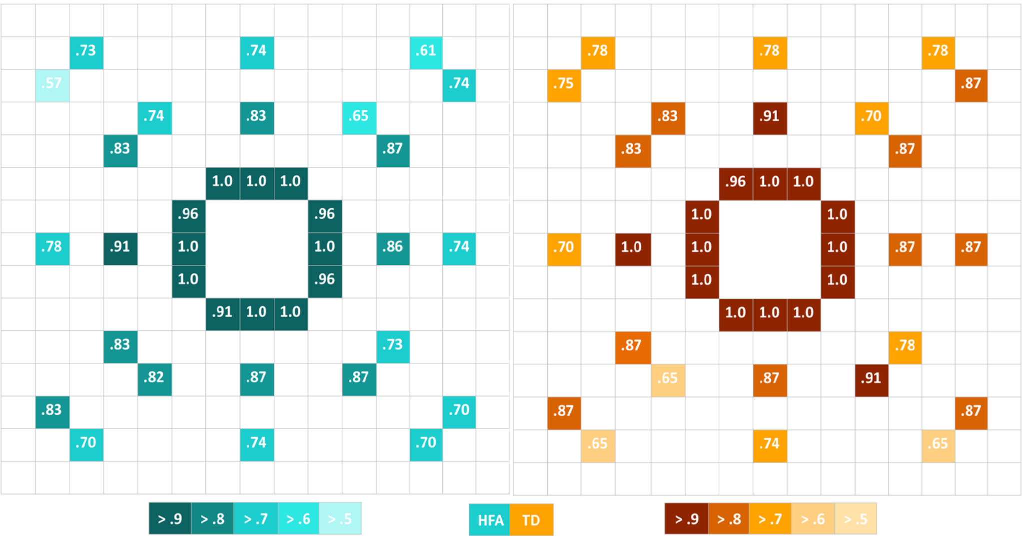


Fig. 4. Proportions of correct responses for all 36 locations around the reference object separately for HFA group (left panel) and TD group (right panel). The color-coding corresponds to the level of accuracy (the darker the square, the higher memory accuracy).

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[2] Due to skewed distribution of the accuracy scores in the OnAxis trials, we re-ran the analysis using non-parametric tests. The results were consisted with the ANOVA outcome: there was no significant difference in accuracy rates between Vertical and Horizontal trials, (Wilcoxon Signed-Rank test, Z = 127, $p = .405$), nor a significant Group difference (Mann Whitney U tests, all $p > .81$).

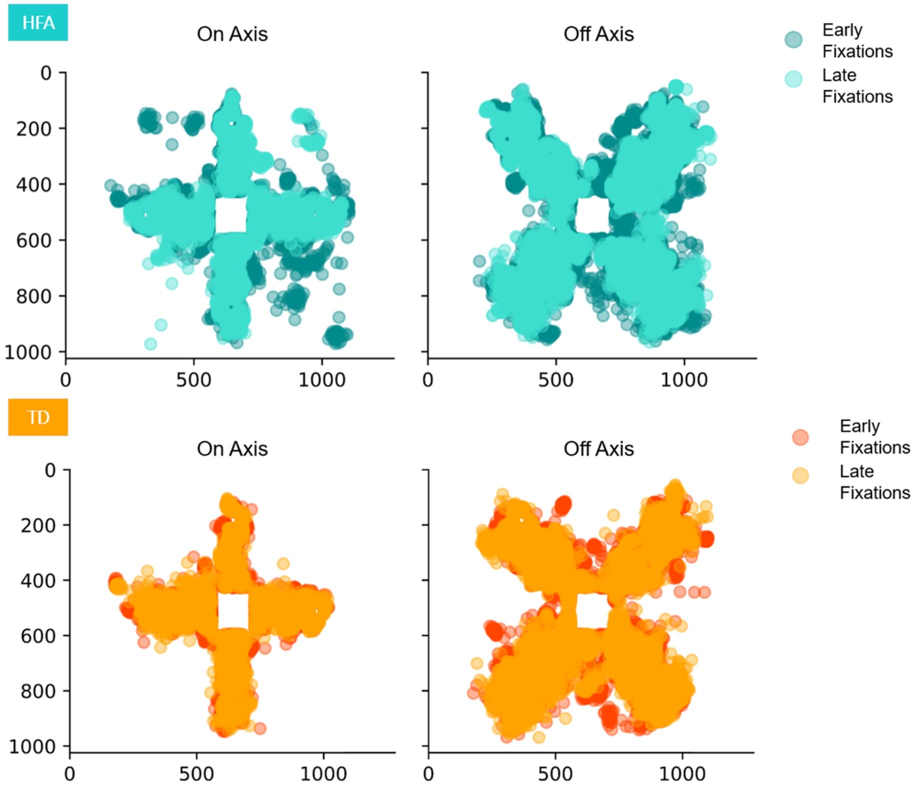

Fig. 5. The distribution of Early and Late fixations in the spatial memory retrieval in OnAxis and OffAxis trials, separately for the HFA (top panel) and TD (bottom panel) participants, showing no differences in gaze behavior between the groups (as explained in text). X and Y axes represent the computer screen coordinates (1280 × 1024).

(the second half of the time from retrieval onset to participant's response). Next, we calculated the average proportions of Early and Late non-target fixations for OnAxis and OffAxis trials across two distances: 2 and 4 squares away from the Reference object (Contact locations were excluded here as well in order to keep the analyses on the accuracy and gaze data consistent). We ran a 2 (Axis: OnAxis, OffAxis) × 2 (Distance: 2, 4) × 2 (FixationType: Early, Late) × 2 (Group: HFA, TD) analysis of variance on the calculated proportions. There was no significant Group effect, nor interaction with the Group in the analysis. There was also no significant effect or interaction with the FixationType, indicating that the gaze behavior was similar in the early and late time windows (see Fig. 5 for the distribution of all eye fixations for both groups). The analysis revealed a main effect of Axis, $F(1, 44) = 86.634$, $p < .001$, $\eta^2 = 0.209$, showing that OnAxis locations had a significantly lower number of non-target fixations than OffAxis locations. We also observed a main effect of Distance, $F(1, 44) = 5.113$, $p = .029$, $\eta^2 = 0.015$, with higher number of non-target fixations for the locations further away from the Reference object.

Similar to the accuracy analyses, we also looked at the gaze behavior in the Horizontal vs. Vertical trials (collapsed over distances). We ran a 2 (AxisType: Vertical, Horizontal) × 2 (Group: HFA, TD) analysis of variance on the proportions of non-target fixations. There was no effect of AxisType, $F(1, 43) = 0.137$, $p = .713$, $\eta^2 = 0.001$, nor an effect of the Group, $F(1, 43) = 0.620$, $p = .435$, $\eta^2 = 0.004$, nor interaction of AxisType × Group, $F(1, 43) = 3.51$, $p = .07$, $\eta^2 = 0.052$.

2.5. Discussion

In line with our predictions, the results from the first experiment showed an effect of Axis and Distance on spatial memory. Both HFA and TD participants showed an advantage for remembering locations OnAxis compared to locations OffAxis, similarly to typical children and adults tested in previous studies (Hayward & Tarr, 1995; Landau & Hoffman, 2005; Munnich et al., 2001). Importantly, this advantage was visible not only in the offline responses, eliciting higher accuracy scores for the locations OnAxis, but it was also reflected in participants' gaze behavior. Specifically, both groups made fewer fixations away from the target location when the target was placed along the axes extending from the Reference object compared to the locations that did not fall on one of the axes. Previous studies showed that the position of eye fixations on the empty screen was indicative of online processes underlying retrieval of spatial locations from memory (Hollingworth, 2005; Laeng et al., 2014; Martarelli & Mast, 2013; Renkewitz & Jahn, 2012). Thus, the higher the number of non-target fixations, the more locations other than the target location are considered and the more uncertainty is involved in the retrieval process. Therefore, the higher number of the looks to the incorrect locations in the OffAxis trials suggests that the participants found it more difficult to accurately retrieve OffAxis locations. This indicates that the axial organization in spatial memory results in an advantage for OnAxis regions not only for the outcome of the memory recall but also for the online processes that precede the final response.

Furthermore, we observed an effect of Distance on participants' accuracy and gaze behavior in the current task. The results showed a decrease in accuracy rates with increasing distance from the Reference object, indicating increasing difficulty in the retrieval of spatial location with increasing distance between the Figure and the Reference object. Similarly, we also observed an increase of non-target fixations as a function of distance.

We did not observe any Group effects in either accuracy or gaze behavior, pointing to the intact axial structure in spatial memory in HFA individuals (note that we refer here to intact knowledge at the level of observable performance and not the underlying mechanisms that lead to certain behavioral outcomes). Contrary to the previous findings indicating impairments in spatial working memory in individuals on the autism spectrum (see Lai et al., 2017; Wang et al., 2017), we found intact memory for spatial location in HFA. Crucially, not only the outcome but also the retrieval process preceding the response in the HFA group showed a strikingly similar pattern to the TD group, as indicated by the gaze patterns that were indistinguishable from the controls' eye movements. Many spatial working memory tasks used in the previous studies were more complex, requiring the maintenance of more than one spatial location, an ability that gradually increases with age (e.g. Corsi Block-Tapping Task, where a full sequence of locations has to be correctly repeated, see Farrell Pagulayan, Busch, Medina, Bartok, & Krikorian, 2006). Nevertheless, the successful performance in these types of tasks (such as Corsi Block-Tapping Task) builds on certain prerequisites. One of them is the ability to retrieve the precise spatial location of a Figure object relative to the Reference object. Here we provide the evidence that this ability is spared in HFA individuals.

Furthermore, despite previously reported evidence for atypical gaze patterns in ASD, including in high-functioning individuals (e.g. Papagiannopoulou, Chitty, Hermens, Hickie, & Lagopoulos, 2014; Rigby, Stoesz, & Jakobson, 2016; Wang et al., 2015), we did not observe any significant differences in eye movements between the groups. As the previous investigations tested the gaze patterns in social rather than visuospatial contexts (e.g. using stimuli like images of faces or complex natural scenes), this finding points to the importance of considering the type of visual input when investigating gaze patterns in ASD.

3. Experiment 2: Spatial representation of direction within the axis

In Experiment 2, we investigated the effect of Direction (e.g. left/right) within each axis on memory for spatial location. We predicted that the representation of direction within the same axis was more fragile and therefore more difficult to retrieve compared to the representation of the different axes themselves (Vertical vs. Horizontal). If the representation of direction was indeed more fragile, we predicted poorer performance (i.e. longer response times and higher proportion of non-target eye fixations) on trials in which participants had to compare two locations within the same axis (DifferentDirection condition, e.g. above/below within the Vertical or left/right within the Horizontal) than trials in which they had to compare two locations on different axes (DifferentAxis condition, e.g. Vertical vs. Horizontal). Additionally, if the direction component in spatial memory was compromised due to a developmental deficit, we predicted lower performance in the HFA group compared to the TD group in the DifferentDirection but not in the DifferentAxis condition. Alternatively, if direction discrimination was intact in HFA, we predicted to see no group differences.

3.1. Participants

The same participants as in Experiment 1 participated in the experiment.

3.2. Design and materials

The design included the main, within-subject factor of Condition (DifferentAxis, DifferentDirection) and the between-subject factor of Group (HFA, TD). The DifferentAxis condition involved the comparison of two locations on different axes (Vertical vs. Horizontal) and the DifferentDirection condition required the comparison of two locations within a single axis (above or below within the Vertical; left or right within the Horizontal). Dependent measures included participants' offline responses (proportions correct key presses), reaction times, and eye movements (proportions of non-target fixations).

The stimuli included images of the Reference object (blue square) and the Figure object (red circle), similar to the stimuli used in Experiment 1, but with certain adjustments. First, the locations of the Figure object were limited to OnAxis locations (8 locations, 4 on each axis). Second, the circle was located at one of two distances from the Reference object: 1 or 2 squares away (similar to Landau & Hoffman, 2005). We also used the same forced-choice method as in the original study (Landau & Hoffman, 2005). Thus, pictures matching the encoding image (Same) were paired with non-matching ones (Different). In the non-matching picture, the circle was placed either on DifferentAxis (e.g. Vertical instead of Horizontal) or in DifferentDirection (e.g. Horizontal Left instead of Horizontal Right) compared to the original location in the encoding image.

There were 16 DifferentAxis trials (8 per Distance) and 16 DifferentDirection trials (8 per Distance) in the experiment, each shown twice with the position of the correct (matching) picture counterbalanced between the left or right side (64 trials in total).

3.3. Procedure

The participants were told that their task would be to remember the red circle's location in relation to the blue square, but this time they would choose one of two pictures where the circle was in the same location. Similar to Experiment 1, we showed examples of what the stimuli might look like in the task and conducted a short practice session. Because we collected both offline and online responses, the practice session was followed by the calibration procedure for the eye-tracking and then the main part of the experiment (see Fig. 6). Each trial started with a fixation cross followed by a short presentation of the encoding image (300 ms) on top of the screen, a mask, a 1000 ms delay and the retrieval phase with the two alternatives side to side on the bottom of the screen: a matching picture (Same) and a non-matching picture (DifferentAxis or DifferentDirection). The alternatives were misaligned in order to disrupt any effects of their being horizontally aligned. The order of the 64 trials was fully randomized. Participants responded by pressing one of two keys on a response box. They were asked to choose one of the alternatives by pressing on a key that was on the same side as the picture they wished to choose (the experimenter showed by pointing which key corresponded to which side of the screen without using words *left* or *right*). Participants were also asked to give the response as quickly as possible and during the practice session they were given feedback about their accuracy and response time to motivate high performance in the task.

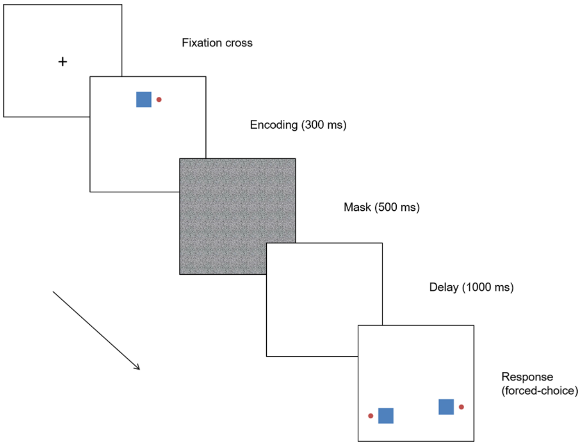

Fig. 6. The structure of the trial in Experiment 2: fixation cross, encoding phase, a mask, a short delay and retrieval phase.

3.4. Results

Similar to Experiment 1, we conducted the analysis in two main steps: first looking at the offline responses and subsequently at the online measures. The main focus of the analyses was the effect of Condition (DifferentAxis vs DifferentDirection) on participants' response times and the proportions of non-target eye fixations, i.e. eye fixations directed to the foil and not to the matching picture during the retrieval phase.

The participants' accuracy was at ceiling (M = 0.95), and there were no significant differences in the accuracy scores between the groups (Mann-Whitney U test, all $p > .22$) or between the DifferentAxis and DifferentDirection conditions. We proceeded with the analysis on the response time data.

Response time data. Response times that exceeded three standard deviations from the mean (calculated separately for each Group) were excluded from the analysis (1% of all trials in each Group). The remaining values were log-transformed (base 10log transformation) in order to reduce skewness in the distribution. Response time data from the incorrectly answered trials were removed from the analysis. We ran a 2 (Condition: DifferentAxis, DifferentDirection) × 2 (Group: HFA, TD) analysis of variance on the transformed data. The analysis revealed a main effect of Condition, $F(1, 45) = 30.337$, $p < .001$, $\eta^2 = 0.408$, with significantly

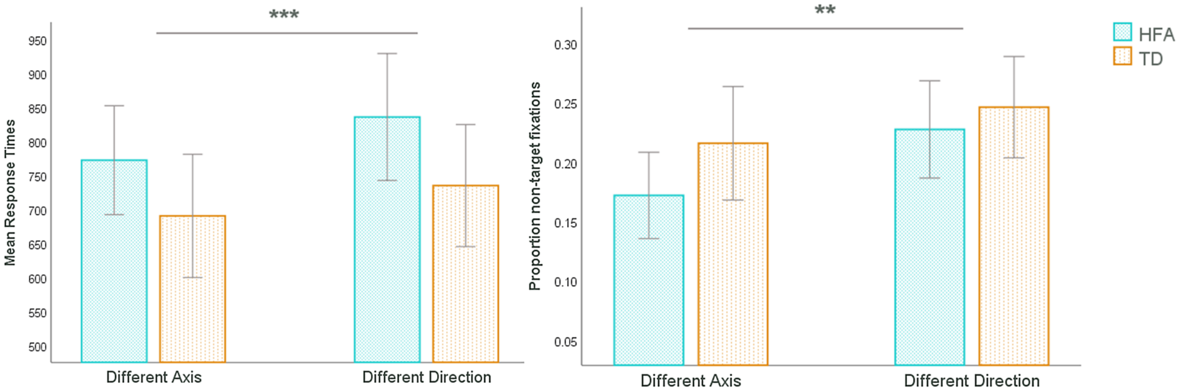

Fig. 7. The effect of Direction on participants' response times and non-target fixations (Late Fixations) in spatial memory retrieval. The DifferentDirection condition elicited longer response times (left panel) and higher proportion late looks to the foil (right panel) in both groups. Error bars represent ± 2 SEM; $^{**}p < .01$, $^{***}p < .001$.

longer responses in the DifferentDirection trials (M = 785 ms) compared to DifferentAxis trials (M = 731 ms). That is, participants took longer time to identify the correct direction within the same axis compared to the location on a particular axis (see Fig. 7). Next, we investigated whether there was a difference in performance between direction within Vertical compared to Horizontal axis. We ran a 2 (AxisType: Vertical, Horizontal) × 2 (Group: HFA, TD) analysis of variance and observed a main effect of AxisType, $F(1, 45) = 22.486$, $p < .001$, $\eta^2 = 0.337$, showing that Horizontal trials elicited longer response times (M = 825, SD = 34.9) compared to the Vertical trials (M = 749, SD = 33.2). Finally, there was no Group effect, nor interaction of Condition and Group in the analyses (all ps > 0.09), indicating that the HFA group showed similar representation of direction to the TD group.

Gaze data. We obtained eye fixations to two Areas of Interest around the response alternatives in the retrieval phase: the matching picture and the foil. As in Experiment 1, the gaze data from one participant was excluded due to technical difficulties during the calibration and the recording. We proceeded with the analysis on the gaze data from the remaining 45 participants. We calculated the average proportions of non-target fixations, i.e. looks to the foil picture during the retrieval phase. As in Experiment 1, the non-target fixations were collapsed into two FixationType categories: Early Fixations (the first half of the time from retrieval onset to the participant's response) and Late Fixations (the second half of the time from retrieval onset to participant's response). We ran a 2 (FixationType: Early, Late) × 2 (Condition: DifferentAxis, DifferentDirection) × 2 (Group: HFA, TD) analysis of variance on the proportions of non-target fixations and observed a main effect of FixationType, $F(1, 44) = 340.54$, $p < .001$, $\eta^2 = 0.887$, indicating overall significantly fewer looks to the foil in the second half (M = 0.215) compared to the first half (M = 0.508) of the retrieval phase. We also observed a main effect of Condition, $F(1, 44) = 6.301$, $p = .016$, $\eta^2 = 0.128$, with reliably more non-target fixations in the DifferentDirection compared to DifferentAxis trials, suggesting that discrimination of direction within the same axis elicited more looks to the foil. Thus, discrimination of direction was more difficult than discrimination of the Vertical vs. Horizontal axis (see Fig. 7). The analysis showed also a significant interaction of FixationType × Condition, $F(1, 44) = 5.772$, $p = .021$, $\eta^2 = 0.111$. Post hoc comparisons (with Bonferroni correction) showed that the difference between the DifferentAxis and DifferentDirection conditions was significant only in the Late and not Early non-target fixations, $t = -3.458$, $p = .005$. This means that the difference between the conditions emerged in the second half of the retrieval phase, right before the response. Finally, there was no significant Group effect, nor interaction with Group in the analysis (all ps > 0.09).

3.5. Discussion

The results showed that, as predicted, the DifferentDirection condition, i.e. discriminating locations within an axis, elicited longer response times and higher proportion of non-target fixations compared to the DifferentAxis condition. This means that correctly identifying direction within the axis (left/right) is secondary to discriminating between the axes (vertical/horizontal) in spatial memory. More specifically, when representing direction (e.g. Left), the representation of the axis (Horizontal) has to be accessed first, followed by the correct choice of the direction within that axis (Left or Right). This two-stage process was reflected in longer response times and more looks to the foil in DifferentDirection condition compared to DifferentAxis condition. The findings are consistent with previous observations indicating that direction is a secondary and more fragile component of spatial representation compared to the primary axial structure. For example, Landau and Hoffman (2005) observed that younger children as well as individuals with Williams syndrome frequently made directional errors while still showing a fundamental axial structure in spatial memory. Likewise, a case study on a high-functioning individual with another type of a developmental deficit, which results in impaired visual localization, also reported selective effects on the directional component of location but preservation of the axial component (McCloskey & Rapp, 2000; McCloskey et al., 1995). A similar phenomenon of stronger representation of axis and weaker representation of direction has been observed in spatial attention tasks in typical adults (Logan, 1995) and in priming studies on reference frame selection (Carlson-Radvansky & Jiang, 1998).

We also observed an effect of AxisType in the context of direction discrimination: discrimination of direction was more difficult in the Horizontal trials than Vertical trials. Participants took a longer time to respond in the DifferentDirection condition when the target location and the foil were located on the horizontal axis compared to when they were located on the vertical axis. This finding is consistent with previous observations of a disproportionate weakness along the horizontal axis in Williams syndrome that is reflected both in language and memory (Landau & Hoffman, 2005), suggesting that discrimination between 'left' and 'right' directions is overall more challenging compared to discrimination between 'above' and 'below' directions. Consistent with that, complete acquisition of spatial terms *left* and *right* is acquired late in development and is preceded by other axial terms like *above/below* or *front/back* (Durkin, 1981; Harris & Strommen, 1979; Harris, 1972; Kuczaj & Maratsos, 1975; Piaget & Inhelder, 1956).

Finally, we did not observe any group differences, neither in the response time data nor in the proportions of non-target fixations. The HFA group responded similarly to controls both in the DifferentAxis and DifferentDirection condition and showed similar eye movement patterns to the TD group across conditions. Specifically, both groups took longer time to respond and made more looks to the foil when it was located within the same axis but in a different direction relative to the target compared to when it was located on a different axis. While these results indicate that directional representation in spatial memory might be intact in the HFA group, it is also possible that a more difficult task could reveal group differences. Even though in the original study by Landau and Hoffman (2005), individuals with Williams syndrome still performed significantly worse in the easiest version of the task (when controls' scores were at ceiling), average accuracy rates are often not sensitive enough to detect subtle deficits. However, the fact that more sensitive measures applied in the current task, such as response times or tracking online gaze behavior, did not reveal group differences suggests that direction component in the non-linguistic system is indeed intact in HFA.

4. Experiment 3: Spatial language production

Experiment 3 investigated the production of spatial terms in the axial reference system. We predicted the effects of Axis and

Table 2
The list of basic axial terms in Norwegian and their English equivalents.

	Norwegian	English equivalent
Vertical Positive	*Over*	*Above/over*
	Ovenfor	*Above/over*
	Oppå	*Top*
	Top	*Top*
Vertical Negative	*Under*	*Below/under*
	Nedenfor	*Below/under*
	Underside	*Underneath*
	Bunn	*Bottom*
Horizontal Left	*Venstre*	*Left*
Horizontal Right	*Høyre*	*Right*

Direction on participants' productions. Specifically, if the locations along the Reference object's axes served as anchors for 'basic axial terms' (i.e. monolexemic spatial terms describing locations along the vertical and horizontal axes, e.g. *above*, *below*, *left*, *right*; see Table 2 for the full list of basic axial terms in Norwegian and their English equivalents), we predicted that we would see shorter productions and higher proportions of basic axial terms in OnAxis compared to OffAxis trials. We also predicted the effect of Direction on the productions, i.e. more frequent confusions of direction within the axis (e.g. *left* instead of *right*) compared to the confusions across axes (e.g. *left* instead of *above*). We predicted there would be no effect of Distance from the Reference object, based on previous findings showing that categorical coding of spatial terms along axes compared to more fine-grained coding in non-linguistic spatial system (Hayward & Tarr, 1995; Landau & Jackendoff, 1993; Talmy, 1983). Finally, if the representation of direction within each axis, compared to the axes themselves, was compromised in language in HFA, we predicted a higher proportion of directional errors in HFA compared to the TD group. Alternatively, if the linguistic representation of direction was intact, we predicted there would be no difference in directional errors between the groups.

4.1. Participants

The same participants as in Experiment 1 and 2 participated in the experiment.

4.2. Design and materials

The experimental design included within-subject factors of Axis (OnAxis, OffAxis), AxisType (Horizontal, Vertical) and Distance (2 squares away, 4 squares away from the Reference object), as well as a between-subject factor of Group (HFA, TD). Dependent measures included proportions of spatial terms productions. Thus, only offline responses (participants' verbal responses) were collected in the current experiment.

The stimuli included the same set of images as in Experiment 1: 36 pictures of the Figure object (red circle), which was shown in 36 target locations around the Reference object (blue square). Each of the locations was shown only once (see Fig. 2). During Experiment 3, no eye movement data was obtained, but the task stimuli were shown on the same monitor screen as in Experiment 1 and 2.

4.3. Procedure

Participants were told that they were going to talk about where the red circle was located in relation to the blue square, and were instructed to respond as if they were filling the gap in the sentence "Sirkelen er __ firkanten" ("The circle is ___ the square"). After these instructions, examples of the stimuli appeared, followed by a short practice session (7 trials showing other than the 36 target locations used in the test). The main part of the experiment consisted of 36 trials, where the participants saw a fixation cross, followed by a sentence with the gap ("Sirkelen er __ firkanten") and a stimulus image of the square and the circle in one of the 36 target locations (see Fig. 8). During the stimulus presentation, participants' task was to name the circle's location out loud. When the response was given, the experimenter proceeded to the next trial. All productions were recorded.

4.4. Results

All recorded productions were transcribed by an independent transcriber. Transcribed responses were coded for the presence of axial terms (Vertical Positive, e.g. "oppå" [on top of], Vertical Negative, e.g. "under" [under], Horizontal Left, e.g. "til venstre for" [to the left of], Horizontal Right, "til høyre for" [to the right of], Horizontal Neutral, e.g. "ved siden av" [beside]), and the presence of non-axial terms (Proximity, e.g. "nær" [near], Contact, e.g. "inntil" [adjacent] and Other, e.g. "på skrå" [diagonally]). Similar to Hayward and Tarr's study (1995), the first spatial term used to describe the circle's location was coded as the primary term. Remaining categories were either Uncodable (0.5%, e.g. "bra distanse" [good distance]) or Missing (1.5%). Following our predictions, we first looked at the axial effects on participants' productions, i.e. differences between productions for OnAxis vs OffAxis

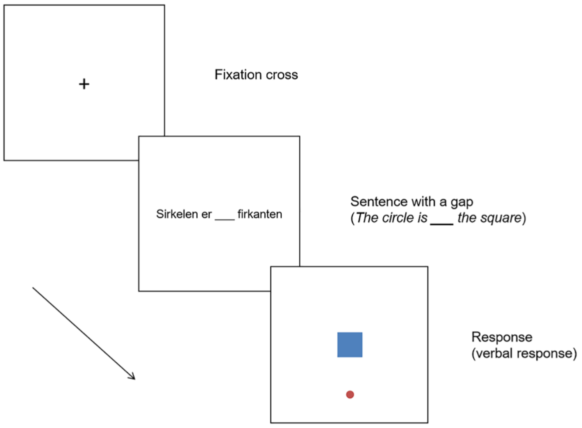

Fig. 8. The structure of the trial in Experiment 3: fixation cross, followed by a prompt sentence with a gap, and the stimulus image. Participants gave a verbal response (e.g. "The circle is under the square"). All participants' responses were recorded.

locations and proportions of target axial terms for locations along the Vertical and Horizontal axes. Next, we looked for an effect of distance from the Reference object (0, 2, 4) on the productions. Finally, we compared different direction and different axis errors in the productions. In the follow-up, exploratory analyses, we examined responses other than axial terms and developmental trajectories of error patterns.

Axial effects. First, we were interested in whether descriptions of locations OnAxis differed in length from the descriptions of other locations. We predicted that descriptions of the OnAxis locations would elicit more productions of basic spatial terms (e.g. *above*, *under*) as those locations are considered to be prototypical for application of these terms. Basic terms are also shorter than other expressions (e.g. *above* vs. *above and to the left*) and hence, high use of these terms in OnAxis trials would result in shorter descriptions. We calculated the average length of the responses (number of words) produced for locations that fell along the vertical or horizontal axis (OnAxis) compared to the locations off-axis (OffAxis), and also included locations in contact with the Reference object (Contact). We ran a 3 (Axis: OnAxis, OffAxis, Contact) × 2 (Group: HFA, TD) analysis of variance on the average number of words in the responses. The analysis revealed a significant main effect of Axis, $F(2, 44) = 80.4, p < .001, \eta^2 = 0.636$. Post-hoc comparisons (with Bonferroni correction) showed that, as predicted, productions were significantly shorter in the OnAxis trials compared to OffAxis trials, $t = -12.13, p < .001$. The analysis also showed that productions in the Contact trials were longer compared to productions in the OnAxis trials, $t = -2.88$, $p = .015$ but shorter compared to OffAxis trials, $t = 9.26$, $p < .001$ (see Fig. 9). There was no significant effect of Group. The results show that locations along the axes evoke shorter responses compared to OffAxis locations or locations in contact with the Reference object. Additionally, locations OffAxis elicited longest of all responses, suggesting that their description required more elaborate productions.

Next, in order to see whether the observed shorter responses to locations OnAxis indeed reflected a general tendency to produce more basic axial terms, we calculated the average proportions of basic axial terms for each participant produced in the OnAxis trials compared to OffAxis trials, as these trials elicited the shortest and the longest productions (i.e. Contact locations were excluded from this analysis). Importantly, all axial terms were included in the analysis (also directional errors, e.g. *to the left* used for the region on the right), in order to see whether the participants mapped axial terms to the correct axes (vertical/horizontal), irrespectively of direction. In addition, the responses to the OffAxis locations frequently included a conjunction of vertical and horizontal basic axial terms (e.g. *top left*, *over to the right*), and were therefore scored separately for Vertical and Horizontal terms. The analysis was thus

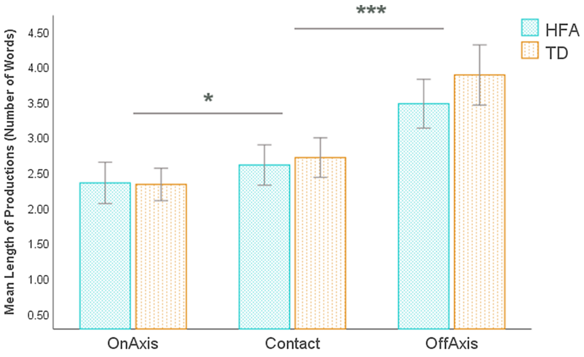

Fig. 9. The effect of Axis on the length of participants' productions in the spatial language task. Naming locations OnAxis evoked significantly shorter productions compared to the locations OffAxis and in Contact with the reference object. Error bars represent ± 2 SEM; $^*p < .05$, $^{***}p < .001$.

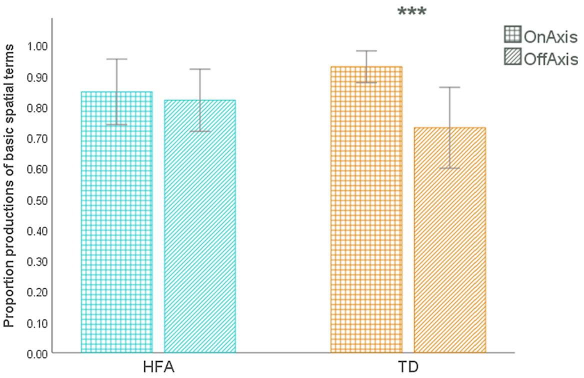

Fig. 10. The interaction of Axis and Group factors in the productions of basic axial terms in Experiment 3. The TD group, but not the HFA group, produced significantly more basic axial terms when naming locations OnAxis compared to the locations OffAxis. Error bars represent ± 2 SEM; ***p < .001.

conducted separately for Vertical and Horizontal regions, each including 4 OnAxis locations (Vertical or Horizontal and 16 OffAxis locations. We first ran a 2 (Axis: OnAxis, OffAxis) × 2 (Group: HFA, TD) analysis of variance on the proportions of basic axial terms produced for Vertical locations. The analysis revealed a main effect of Axis, $F(1, 45) = 13.32$, $p < .001$, $\eta^2 = 0.215$, suggesting that overall, more basic axial terms were used for OnAxis locations compared to OffAxis locations. We also observed a significant interaction Axis × Group, $F(1, 45) = 4.74$, $p = .035$, $\eta^2 = 0.076$. Post-hoc comparisons using Tukey's HSD test revealed that the TD group used significantly more basic axial terms in OnAxis trials compared to OffAxis trials ($p < .001$). However, in the HFA group, proportions of axial terms did not differ between OnAxis compared to OffAxis trials ($p = .726$; see Fig. 10).

Next, because the overall proportions in the previous analysis included also incorrect uses of the basic axial terms (e.g. *to the left* for the Right region), we were interested in whether there were any group differences in the accuracy of the productions. Thus, we calculated the proportions of 'target axial terms' produced in the OnAxis trials. We defined target axial terms as axial terms that were accurate with respect to the direction of the axis (vertical vs. horizontal) and the direction within the axis (e.g. *above* for the upper regions and *to the left* for the Left regions). We ran a 2 (AxisType: Vertical, Horizontal) × 2 (Group: HFA, TD) analysis of variance on the calculated proportions and observed a main effect of Group, $F(1, 45) = 5.39$, $p = .025$, $\eta^2 = 0.109$. The HFA group produced overall significantly fewer target axial terms (M = 0.782) compared to TD group (M = 0.92). The analysis revealed also a main effect of AxisType, $F(1, 45) = 4.63$, $p = .037$, $\eta^2 = 0.095$, showing that Horizontal locations were more difficult to name accurately compared to Vertical locations for both groups (see Fig. 11).

Distance effects. Finally, we asked whether there was an effect of Distance along the axes on participants' productions of *target axial terms*. We calculated the average proportions of the accurate uses of axial terms for locations OnAxis that fell 2 and 4 squares away from the Reference object (collapsed over Horizontal and Vertical trials). We ran a 2 (Distance: 2, 4) × 2 (Group: HFA, TD) analysis of variance on the proportions of target axial terms. The analysis showed that there was no significant effect of Distance on participants' productions, $F(1, 45) = 0.115$, $p = .736$, $\eta^2 = 0.003$, nor a significant interaction of Distance × Group, $F(1, 45) = 1.039$, $p = .314$, $\eta^2 = 0.023$.

In sum, the HFA group produced shorter responses for OnAxis compared to Contact or OffAxis locations, similar to the TD group. However, the number of the productions of axial terms in the HFA group did not differ significantly between OnAxis and OffAxis trials. This suggests that the HFA group produced a similar number of axial terms irrespective of the location (OnAxis or OffAxis) in the axial reference system. When looking at the accuracy of these productions, i.e. the proportions of target axial terms in OnAxis trials, the HFA group showed fewer accurate productions of axial terms compared to TD controls (see Fig. 12. for the complete summary of the average proportions of target axial terms in all locations).

Remaining responses. In order to identify what types of responses the participants gave when *not* using a target axial term, we took all the remaining productions (i.e. other than the correct axial terms) from the task and coded them for the presence of Different Axis terms (e.g. a horizontal term for a Vertical region), Different Direction terms (e.g. *to the left* for a Right region), Proximal and Contact terms (e.g. *far*, *near* or *adjacent*) and Other terms (e.g. *diagonally*). Those categories successfully explained 98% of all responses that were not target axial terms. The remaining 2% consisted of Missing (1.5%) and Uncodable productions (0.5%). The proportions of the responses were calculated separately for Vertical regions (4 OnAxis and 6 Contact locations), Horizontal regions (4 OnAxis and 6 Contact locations) and OffAxis regions (16 locations).

Table 3 shows that the HFA group made more Different Axis and Different Direction errors. However, while Different Direction errors were restricted only to cases when participants wrongly named the direction within the same axis (most frequently when producing horizontal terms, e.g. *to the left* for Right regions), the Different Axis errors were of two kinds. Most of the Different Axis errors in the HFA group were dominated by the use of *in front of* for Vertical Positive regions and *behind* for Vertical Negative regions. Thus, when making those errors, the HFA group was interpreting the Vertical axis as the Front/Back axis and not confusing it with the Horizontal axis. The *front/back* terms made up 69% of all Different Axis errors in the HFA group and were not present in the control group. It is important to note, however, that these errors were limited to only 5 individuals in the HFA group. In the remaining Different Axis errors (restricted only to two subjects), participants used a vertical term to name a Horizontal region or a horizontal term to name a Vertical region.

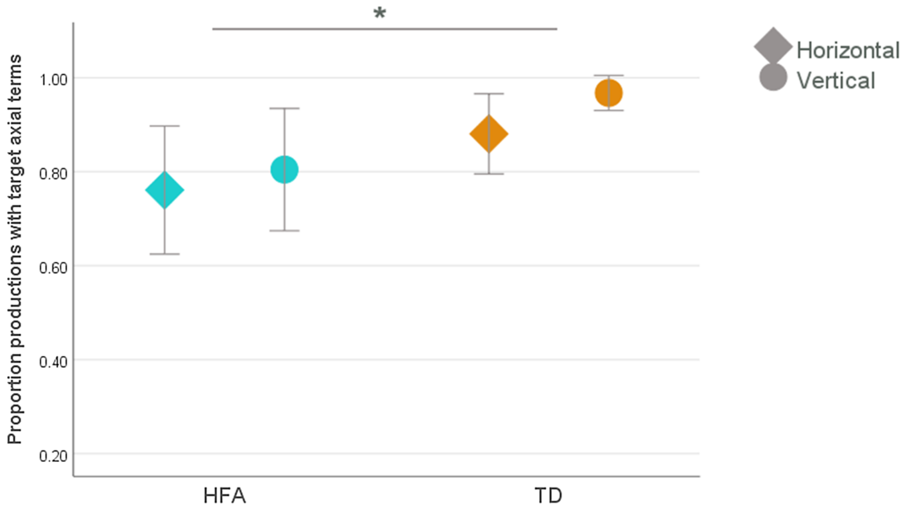

Fig. 11. The main effect of Group and AxisType on the productions of *target axial terms*. Naming locations on the Horizontal axis evoked overall lower number of target axial terms and the HFA group produced significantly fewer accurate axial terms compared to TD. Error bars represent ± 2 SEM; *p < .05.

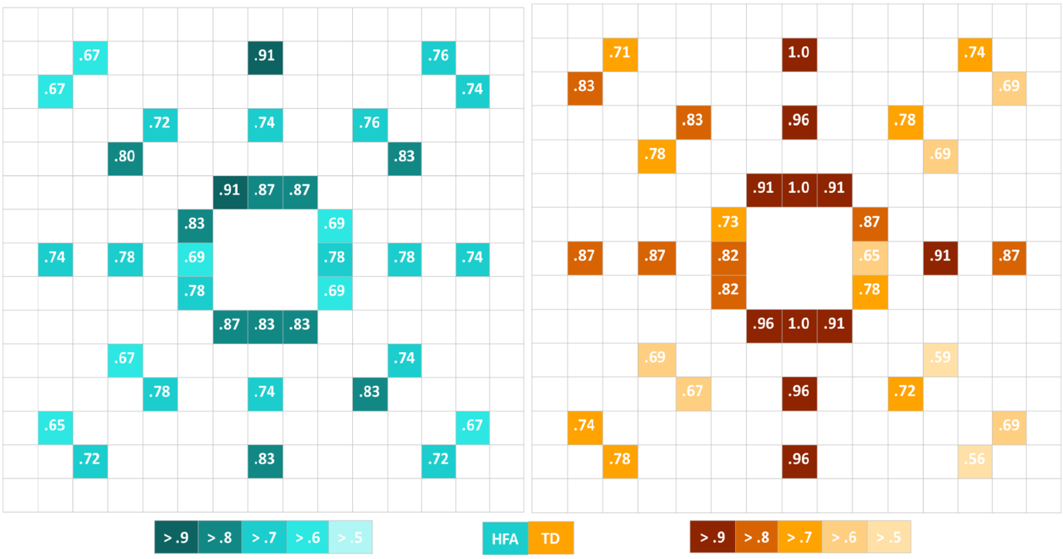

Fig. 12. Proportions of target axial terms produced in all 36 locations around the reference object (Experiment 3; left panel: HFA group, right panel: TD group). The color-coding corresponds to the proportion of target axial terms occurrence (the darker the square, the higher proportion of target axial term productions for that location).

Table 3
Proportions of remaining productions (i.e. other than target axial terms).

	Vertical regions		Horizontal regions		OffAxis Regions	
	HFA	TD	HFA	TD	HFA	TD
Different Axis	0.07	0.00	0.03	0.01	0.03	0.00
Different Direction	0.00	0.00	0.04	0.02	0.11	0.02
Proximal/Contact	0.02	0.02	0.07	0.11	0.07	0.09
Other	0.06	0.02	0.09	0.04	0.09	0.18
Total	**0.15**	**0.04**	**0.23**	**0.18**	**0.30**	**0.29**

The other two categories of responses (Proximal/Contact and Other) consisted of more general terms, like *near* or *far*, and *diagonally* or *in the middle*. Table 3 shows that, when looking at the overall proportions, HFA used somewhat fewer Proximal/Contact terms and a similar number of Other terms compared to the controls. However, the pattern of distribution of Other terms was slightly different depending on the condition: the table shows that the HFA group showed a tendency to use these terms more in OnAxis trials (M = 0.08), while the control group used them more frequently in the OffAxis trials (M = 0.18).

Error patterns. As the last step in the exploratory analysis of the production data, we looked more closely at the two error patterns that were most pronounced in the HFA group: Different Direction and Front/Back errors. We calculated the total number of the errors across all trials and compared the average proportions of Different Direction and Front/Back errors between the groups (using the Mann-Whitney U test for independent samples). The analysis showed that the HFA group indeed made significantly more Different Direction errors, $U = 185$, $p = .05$, and Front/Back errors, $U = 207$, $p = .02$, compared to the controls. Next, we inspected how the tendency to make a directional or Front/Back error changed with age in both groups. Due to a sample size of 46 participants with a wide age range and hence, only few data points per age, we collapsed the proportions into two age categories. We created a category including Children/Adolescents (participants under 18 years old, N = 20) and Adults category (participants over 18 years old, N = 26). Children/Adolescents in the HFA group showed the highest proportion of both Different Direction and Front/Back errors (HFA = 0.19, TD = 0.02). However, the pattern of errors in Adults with HFA was almost indistinguishable from the control group (HFA = 0.05, TD = 0.02). Indeed, the Mann-Whitney U test showed a significant difference between the age groups in the HFA sample, $U = 32$, $p = .02$, but not in the TD sample, $U = 65$, $p = 1.0$. Thus, while the error rate was stable (at floor) across ages in the control group, the HFA group showed a decrease in production errors with increasing age.

Finally, we investigated whether the tendency to make directional or front/back errors in spatial language productions was associated with participants' verbal abilities (due to high heterogeneity in the verbal abilities in HFA group, see Table 1). We ran a Spearman correlation between the proportions of Different Direction and Front/Back errors and background measures of language abilities. Neither Verbal Comprehension nor Morphological Comprehension was correlated with the proportions of errors in the production task ($-0.004 > r_s > -0.17$; $0.98 > p > .26$).

4.5. Discussion

Experiment 3 showed that the HFA and TD groups did not differ in the length of their productions; however, the groups showed significant differences in the productions of basic and target axial terms. Locations along the axes (OnAxis) elicited shorter responses than Contact and OffAxis locations, suggesting that they were named effortlessly, serving as the prototypical regions for the descriptions of spatial locations in the axial reference system. The fact that Contact locations elicited longer responses than OnAxis but shorter responses than OffAxis locations, indicates that immediate contact with the Reference object gives an advantage in the descriptions of spatial locations, while still eliciting occasional use of more elaborate descriptions.

In TD individuals, these shorter productions in the OnAxis trials reflected the tendency to use basic axial terms more frequently than in the OffAxis trials, which is consistent with the previous observations of the effect of Axis on spatial language (Hayward & Tarr, 1995; Landau & Hoffman, 2005; Munnich et al., 2001). However, the frequency of the productions of basic axial terms in the HFA group did not differ between OnAxis and OffAxis trials. That is, HFA individuals used basic axial terms to describe the locations along the axes as frequently as when describing other locations. The reason for this voluntary use of axial terms, which are not obligatory for the locations OffAxis, might result from the omissions of proximal terms. Recent research has shown that HFA individuals can have difficulties with proximal terms such as *near* and *far* (see also the use of *here* and *there* in Hobson, García-Pérez, & Lee, 2010) and show a tendency to omit them in the descriptions of spatial layouts (Bochynska, Coventry, Vulchanov, & Vulchanova, 2019). Indeed, when looking at the proportions of the non-axial productions in the current experiment, the HFA group showed somewhat fewer productions of proximal terms compared to the TD group. Avoiding the use of these terms can affect the available range of words when naming locations in the axial reference system, because proximal terms have been shown to be one of the best candidates for naming spatial relationships after basic axial terms. For example, in Landau and Hoffman (2005) study, individuals with Williams syndrome showed frequent substitutions of proximal terms and other non-axial terms for the axial terms. Thus, a tendency to omit the proximal terms or insistence on using axial terms irrespective of the position OnAxis or OffAxis can result in an increased number of axial terms, even at the cost of higher number of errors.[3] Indeed, we observed significantly more incorrect productions of the axial terms in HFA compared to TD. Most importantly, the HFA group showed significantly higher proportions of directional errors compared to the TD group, which suggests that direction representation in language is especially weak in HFA.

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[3] Another possibility is that, as individuals with ASD display rigid language patterns, repetitive behaviors and insistence on sameness (American Psychiatric Association, 2013) that can result in difficulties in changing strategies (see Geurts, Corbett, & Solomon, 2009 for the discussion on cognitive flexibility), they might have chosen to use similar terms consistently across the whole task. Such a tendency could overrule the typical bias to use more axial terms along the axes and fewer axial terms outside the axes.

Note, however, that although the main effects of the Axis in the language productions in both groups were robust (see the eta squared values in the reported results), the directional errors were more variable (displayed by 13 out of 25 individuals with HFA in the current sample, predominantly children and adolescents).

Among the erroneous productions, we also observed substitutions of vertical terms with *front/back* terms in HFA group, a pattern of responses that was not present in the Williams syndrome data reported before. Five individuals in the HFA group, but not a single participant in the TD group, used *front/back* instead of *above/below* terms for locations along the vertical axis. Even though there is relatively little evidence on how typical these exact types of errors are in young children, previous studies did show that children (ca 3–7 year olds) might substitute vertical terms with *front/back* terms or choose an object's front or back as their top or bottom (Clark, 1980; Leikin, 1998). This suggests that even though the substitutions of vertical terms with *front/back* terms were not present in the current TD sample, they are in the range of typical uses that occur early in development. Moreover, it shows that the confusions of front/back and vertical axes might be a common error, unlike the front/back-horizontal or vertical-horizontal confusions. Importantly, the majority of the axial errors observed in the current HFA sample were limited to these common front/back-vertical substitutions, suggesting a quantitative rather than qualitative nature of these errors. Finally, because the acquisition of *front/back* terms shows a generally protracted and complex learning trajectory (Cox & Ryder Richardson, 1985; Harris & Strommen, 1979; Johnston, 1984; Kuczaj & Maratsos, 1975), this might reflect some degree of uncertainty in children's uses of those terms (Durkin, 1981). Indeed, the Reference object in the current set of stimuli, which was a plain square, was ambiguous with regard to the top or front side (unlike in the original study by Hayward & Tarr, 1995, where the Reference object had a marked top and bottom side). Thus, HFA participants could choose to apply the *front/back* terms as a result of this ambiguity. Nevertheless, the exact mechanism underlying the tendency to substitute vertical with *front/back* terms in HFA is not clear and further research will need to determine in what contexts and why they appear.

Lastly, we also observed that horizontal locations were more difficult to name accurately compared to vertical locations in both groups of participants overall. Horizontal trials elicited higher proportions of directional errors (i.e. the confusions of the terms *left* and *right*), which is consistent with several studies mentioned earlier that reported later acquisition of horizontal terms, compared to vertical and *front/back* terms in typical development (Durkin, 1981; Harris & Strommen, 1979; Harris, 1972; Kuczaj & Maratsos, 1975; Piaget & Inhelder, 1956).

5. Experiment 4: Spatial language comprehension

In the last experiment, we investigated spatial language comprehension in the axial reference system. Specifically, we asked how accurately HFA participants map spatial terms onto the relevant spatial locations (in comparison to the TD group) in a task where, after seeing a sentence with a spatial term, participants were to click on a corresponding location on the screen. We expected to see the effects of both Axis and Direction on responses. More specifically, we predicted that the locations selected for the axial terms would cluster along the relevant halves of the vertical and horizontal axes, e.g. above/below or right/left. We also expected to see two types of errors in the processing of spatial terms: Different Direction errors, e.g. clicking on or looking at the Right region in response to *til venstre for* ("to the left of"), and Different Axis errors, e.g. clicking on or looking at the Right region in response to *nedenfor* ("below"). Finally, we predicted that if direction discrimination was more fragile in HFA spatial language than in TD spatial language, the HFA group would show a higher number of Different Direction errors. Alternatively, if direction discrimination was intact in language in HFA, there should be no difference in directional errors between the groups.

5.1. Participants

Participants were the same as in Experiments 1, 2, and 3.

5.2. Design and materials

The design included the main within-subject factor of AxisDirection (Vertical Positive, Vertical Negative, Horizontal Left, Horizontal Right) that allowed for investigating four main directions that directional spatial terms map onto in the axial reference system. Additionally, as in the previous experiment, there was one between-subject factor of Group (HFA, TD). We collected both offline (mouse clicks to relevant locations on the screen) and online (eye fixations) responses, where we looked at two types of errors made to non-target areas: DifferentAxis and DifferentDirection.

There were in total 26 trials in the experiment: nine with Vertical Positive terms, 9 with Vertical Negative terms, 4 with Horizontal terms that specify direction (Left or Right), 2 with Horizontal Neutral terms, and 2 with Contact terms (see Table 4). Note that some of the spatial terms categorized as Vertical also indicated contact, e.g. *oppå* ("on top of") or *på bunnen av* ("on the bottom of"). However, their location was still restricted to the Vertical Positive or Negative area, compared to neutral Contact terms like *inntil* ("adjacent"), and hence they were included in the Vertical and not Contact category.

Table 4
The complete list of linguistic stimuli in Experiment 4.

	Norwegian	English equivalent
Vertical Positive	*Over*	*Above/over*
	Ovenfor	*Above/over*
	Langt over	*Way above/over*
	Langt ovenfor	*Way above/over*
	Rett over	*Right above/over*
	Rett ovenfor	*Right above/over*
	Høyere enn	*Higher than*
	Oppå	*On top of*
	På toppen av	*On the top of*
Vertical Negative	*Under*	*Below/under*
	Nedenfor	*Below/under*
	Langt under	*Way below/under*
	Langt nedenfor	*Way below/under*
	Rett under	*Right below/under*
	Rett nedenfor	*Right below/under*
	På underside av	*Underneath*
	På bunnen av	*On the bottom of*
	Lavere enn	*Lower than*
Horizontal Left	*Til venstre for*	*To the left of*
	På venstre siden av	*On the left side of*
Horizontal Right	*Til høyre for*	*To the right of*
	På høyre siden av	*On the right side of*
Horizontal Neutral	*Ved siden av*	*Next to, beside*
	På siden av	*On the side of*
Contact	*Inntil*	*Touching, adjacent*
	Rett ved siden av	*Right to*

5.3. Procedure

The participants were told that they would see sentences telling them where the red circle was and then, they would have to click on the screen where they thought this location was. After a short practice session (3 trials) and successful calibration for recording the eye movements, the main part of the experiment started. Each trial consisted of a fixation cross, followed by a sentence in Norwegian that described the location of the circle, e.g. "Sirkelen er **under** firkanten" ("The circle is **under** the square"), followed by a picture of a blue square in the middle of the screen (the reference object; see Fig. 13). The participant's task was to place the circle in relation to the square as described in the sentence by navigating the mouse cursor and clicking on the chosen location. The answers were collected by mouse clicks to the 280 Areas of Interest (AOIs) that formed a grid surrounding the Reference object (see Fig. 2; as in the previous experiments, the grid was not visible to the participants). In addition, we obtained the eye movement data from the response phase, defined as the time from the Sentence offset to the participant's mouse click response.

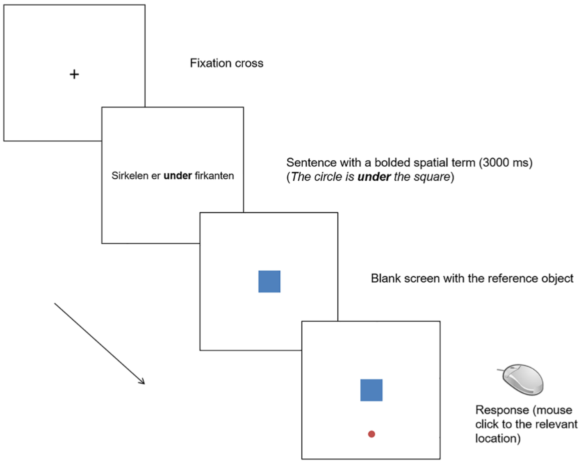

Fig. 13. The structure of the trials in Experiment 4: fixation cross, a sentence with one of the spatial terms, and a blank screen with the reference object followed by the response.

5.4. Results

As in Experiment 1 and 2, we first looked at the offline responses, i.e. mouse clicks to the locations around the Reference object, and then at the online measures, i.e. the participant's gaze behavior during the response phase. As multiple Areas of Interest from the grid could potentially be target areas, i.e. correct responses in the task, we defined broader target areas for all directional spatial terms. Based on the distribution of responses in the Hayward and Tarr (1995) study, for Vertical Positive terms the target areas included the whole region over the Reference object and the extension of its upper edge, for Vertical Negative terms, under the Reference object and the extension of its lower edge, for Horizontal Left terms, the region to the left of the Reference object and the extension of its left edge and for Horizontal Right terms the region to the right of the Reference object and the extension of its right edge (see Fig. 14).

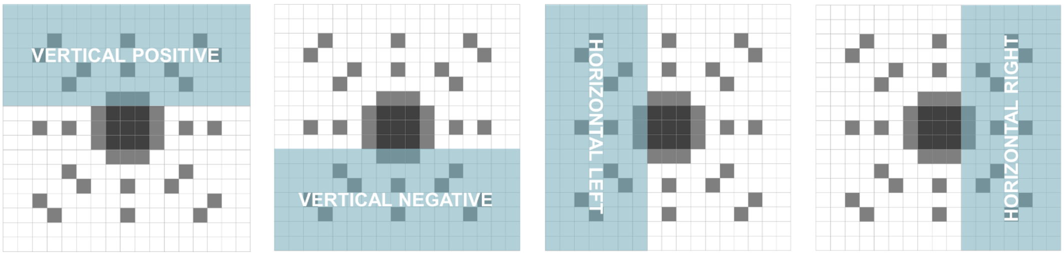

Fig. 14. The main target areas for directional spatial terms in Experiment 4: Vertical Positive (e.g. *above*, *over*), Vertical Negative (e.g. *below*, *under*), Horizontal Left (e.g. *to the left of*), and Horizontal Right (e.g. *to the right of*).

Mouse response data. We first looked at the mouse clicks to the Areas of Interest around the Reference object. Fig. 15 shows the spatial distribution of the participants' mouse clicks on the computer screen separately for Vertical Positive, Vertical Negative, Horizontal Left, Horizontal Right, Horizontal Neutral, and Contact terms superimposed on the screen coordinates. The visual inspection of the graphs shows that the distribution of the responses looks very similar across HFA and TD groups. In addition, even though the Reference object was surrounded only by the white, blank screen, the distribution of the mouse clicks shows that participants organized their responses along the invisible Vertical and Horizontal axes with only little spread and single directional errors. We calculated the average proportions of all directional errors (e.g. mouse click to the Left region after term *to the right of* in the preceding sentence) across groups. The total number of errors was relatively small (M = 0.01) and non-parametric comparisons (Mann-Whitney *U* test) showed that there was no reliable difference between the groups in the proportion of error responses, U = 204.5, $p = .127$.

Gaze data. Next, we looked at the participants' gaze behavior during the response phase. As in Experiment 1 and 2, the gaze data from one participant was excluded due to technical difficulties during the calibration and the recording. Fig. 16 shows the spatial distribution of all eye fixations around the Reference object separately for all groups of spatial terms. Only the fixations from the response phase, i.e. after the offset of the Sentence but before the response, were included in the graph. In addition, as in Experiment 1 and 2, we divided participants' fixations into two categories: Early (the first half of the response phase before the mouse response was given) and Late (the second half of the response phase before the mouse response was given), in order to investigate the temporal changes in the online processing of the spatial terms reflected in the gaze patterns. Visual inspection of the graphs shows that, similar to the mouse responses, the participants eye fixations were organized along the invisible Vertical and Horizontal axes, even though participants were free to inspect the whole screen. However, the distribution of the fixations suggests that the HFA group showed more spread and potentially more non-target fixations, especially in the Early fixations.

Thus, we calculated the proportions of non-target fixations to the DifferentAxis areas and to the DifferentDirection areas (note that the proportions were calculated per participant, per trial, i.e. all reported results are corrected for potential differences in the total number of fixations) and compared them across the groups and the fixations types.

Due to the skewed distributions of the non-target fixations, we ran non-parametric between-groups comparisons (Mann-Whitney U tests with Bonferroni correction). Results showed that compared to the TD group, the HFA group made significantly more fixations to DifferentAxis regions, but not to DifferentDirection regions, during the first half of the response phase (Early Fixations), $U = 345$, $p = .039$. However, the analysis of Late Fixations showed that the HFA group made more fixations to DifferentDirection regions, but not to DifferentAxis regions (compared to the TD group) during the second half of the response phase, $U = 365$, $p = .002$. Fig. 17 shows the development of this trend over time, with fixations to DifferentAxis gradually dropping through the first half of the response phase and fixations to DifferentDirection increasing in the second part of the response phase in the HFA group.

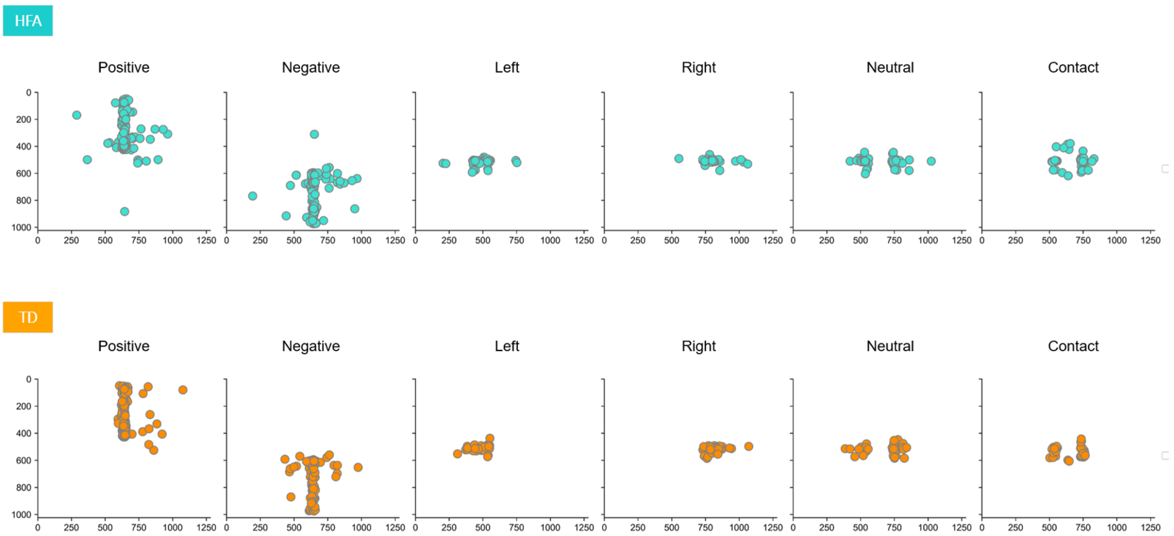

Fig. 15. All mouse click responses superimposed on the background area around the reference object separately for Vertical Positive, Vertical Negative, Horizontal Left, Horizontal Right, Horizontal Neutral and Contact spatial terms. X and Y axes represent the computer screen coordinates (1280 × 1024). Top panel: HFA group, bottom panel: TD group.

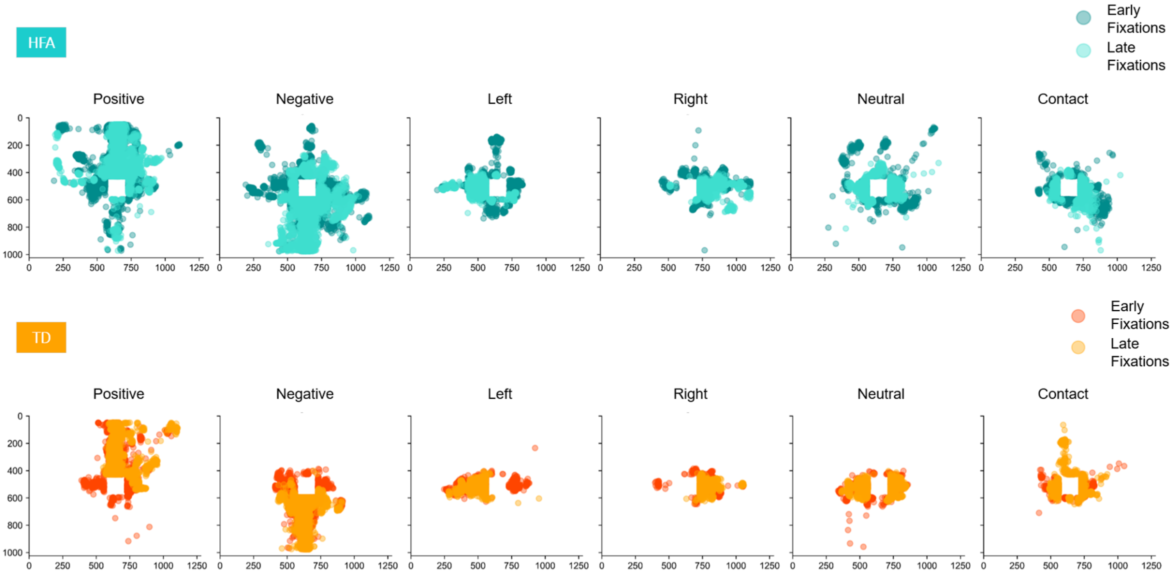

Fig. 16. All eye fixations (Early and Late Fixations) before the mouse click response superimposed on the background area around the reference object separately for Vertical Positive, Vertical Negative, Horizontal Left, Horizontal Right, Horizontal Neutral and Contact spatial terms. X and Y axes represent the computer screen coordinates (1280 × 1024). Top panel: HFA group, bottom panel: TD group.

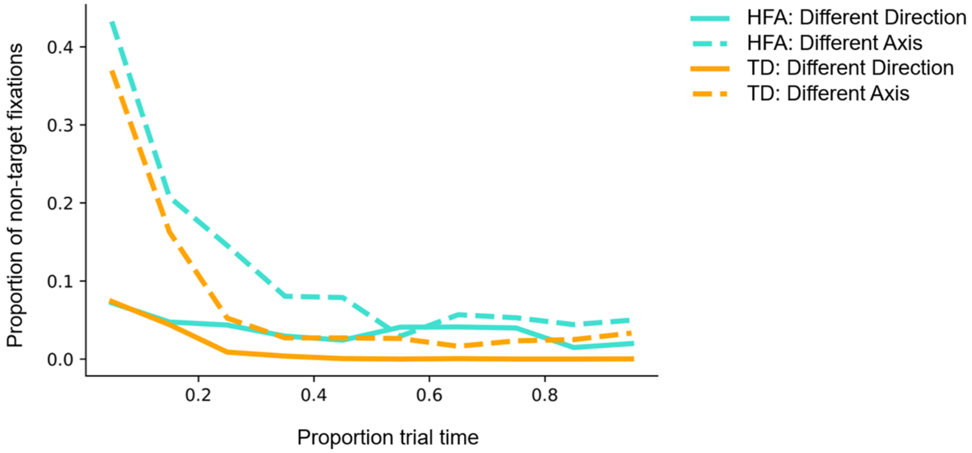

Fig. 17. The proportions of non-target fixations to DifferentAxis and DifferentDirection locations over time (before the mouse click response) separately for HFA and TD groups. Proportion trial time represents relative time from the offset of the Sentence to participant's response, and divided into 10 quartiles.

5.5. Discussion

The results from Experiment 4 showed that the axial reference system supported the comprehension of spatial terms in both TD and HFA groups, as indicated by the clustering of offline responses and eye fixations along the invisible axes extending from the Reference object. The fact that the majority of the mouse clicks following basic axial terms such as *above*, *below*, *left*, *right* fell along the horizontal and vertical axes suggests that these locations serve as the prototypical regions for these terms, in line with previous reports (Hayward & Tarr, 1995; Landau & Hoffman, 2005; Munnich et al., 2001).

Remarkably, we observed the same pattern in participants' gaze behavior. Even though participants could freely move their gaze to inspect the whole screen, most of their eye movements were directed towards those prototypical regions along the axes. This is the first evidence for the real-time processes that take place when people mentally impose the set of axes on the Reference object while processing the meanings of spatial terms, a mechanism discussed before in the literature (see Landau, 2003).

Furthermore, while the patterns of offline responses were indistinguishable between the groups, online measures revealed certain weaknesses in the representations of spatial terms in HFA individuals. Similarly to the previous report on individuals with Williams syndrome (Landau & Hoffman, 2005), HFA group showed noisier representations that might suggest higher uncertainty and less efficiency in the processing of spatial language, as indicated by the distributions of both Early and Late eye fixations. Most importantly, however, HFA individuals showed an orderly pattern in their gaze behavior that might provide new insights into the stages of processing of the spatial terms' meanings. Specifically, HFA individuals made more fixations to Different Axis compared to the controls in the first half of the response phase and subsequently, more fixations to Different Direction in the second part of the response phase. Importantly, the group differences in the looks to Different Axis disappeared by the second part of the response phase, while increased looks to Different Direction persisted in HFA up until the final response. This might suggest that by posing additional demands on the processing of directional terms, a more fragile representation of direction leads to clearer separation of the two distinct stages of the comprehension process that could have been otherwise difficult to observe in typical individuals. In the first stage of that process, the correct axis is being identified while in the second stage the correct direction within that axis is being determined. Contrary to that, the TD participants identified both the correct axis and the correct direction simultaneously within the earlier stages of their response, and in a shorter time than the HFA participants. Future research should investigate whether the presence of these distinct stages is a typical characteristic of spatial language processing early in development, since young children show a weaker representation of direction compared to the adults, or whether it is specific to the HFA (or ASD) population. In sum, although HFA individuals in the current experiment arrived at normalized responses that were indistinguishable from the responses given by the controls, they still displayed subtle deficits in the processing of the meanings of spatial terms, reflected by their gaze behavior.

6. General discussion

The current study provides significant and novel contributions in two main areas. First, it is the first investigation of the relationship between spatial language and non-linguistic spatial system that uses well-known paradigms (Hayward & Tarr, 1995; Landau & Hoffman, 2005) along with online measures, tapping into real-time processes underlying spatial language and memory. Second, the study provides the first evidence for structural correspondences between the non-linguistic spatial representation system and spatial language along with indications that spatial language is somewhat autonomous from non-linguistic spatial representation in intellectually high-functioning individuals with autism. More specifically, the study revealed a well-preserved axial reference system in HFA that was reflected in both non-linguistic and language tasks. However, it also revealed subtle deficits in the spatial language of individuals with HFA.

6.1. Axial structure in language and memory

Axial structure has been shown to play a key role in both spatial memory and the use of spatial terms in language. Here we provide further evidence in support of this claim. In the current study, participants showed better memory performance for locations along the axes as well as higher proportions of basic axial term mappings onto these locations. Importantly, we also observed the effects of Axis on participants' gaze behavior. When recalling spatial locations that fell along the vertical or horizontal axes, participants made fewer looks away from the target compared to the recall of the OffAxis locations. Moreover, the pattern of eye fixations clustering along the invisible axes in the language comprehension task further supports previous hypotheses that people indeed mentally impose a set of axes on the Reference object when processing spatial information in the axial reference system (Carlson-Radvansky & Logan, 1997; Hayward & Tarr, 1995; Landau, 2003; McCloskey & Rapp, 2000). It is important to note here that alternative mappings of space around the Reference object may be relevant for these or other spatial tasks. That is, spatial representations in memory and language could rely on a different underlying structure, for example diagonal angular or radial. Indeed, some have suggested that despite the presence of axial structure in language, the non-linguistic category prototypes of space may be biased towards the diagonal angular locations and not cardinal axes extending from the Reference object (Crawford et al., 2000; Huttenlocher et al., 1991). Nevertheless, we believe that our data strongly suggest that axial structure plays a role in both language and non-linguistic spatial memory—at least in the tasks we used—and that therefore, the two systems do indeed share spatial structure.

In addition, we also observed the effects of Direction in both language and memory, suggesting that direction representation was more fragile than the representation of the axis, in line with previous findings (Carlson-Radvansky & Jiang, 1998; Landau & Hoffman, 2005; Logan, 1995; McCloskey & Rapp, 2000; McCloskey et al., 1995). Specifically, we observed that recall of the correct direction within the axis was more difficult compared to the recall of the correct axis. Similarly, we observed higher proportions of directional errors in spatial language production (e.g. *left* instead of *right*) compared to the confusions of vertical and horizontal axes (e.g. *above* instead of *right*). We also observed that the representation of direction was more fragile along the horizontal compared to vertical axis. That is, both in non-linguistic and language tasks, the discrimination of the horizontal directions was more challenging compared to the discrimination of the vertical directions. More specifically, participants took longer to recall the correct direction within the horizontal axis and made more directional errors when naming the regions in the horizontal trials. This finding is consistent with the observations of a disproportionate weakness along the horizontal axis in both language and memory in Williams syndrome (Landau & Hoffman, 2005) as well as the studies on spatial language acquisition demonstrating that horizontal terms show prolonged learning trajectory and are mastered later than vertical or *front/back* terms (Durkin, 1981; Harris & Strommen, 1979; Harris, 1972; Kuczaj & Maratsos, 1975; Piaget & Inhelder, 1956).

Finally, we also found certain differences between the systems. We observed that participants' memory performance was dependent on the distance from the Reference object, while spatial language coded space categorically (i.e. independently of distance). In sum, the results indicate a close relationship, but not a complete overlap, between spatial language and spatial memory. Both systems displayed a strong axial organization of the representations, where directional component was weaker than the representation of the axes, and direction discrimination along the horizonal axis was more fragile compared to the vertical axis.

6.2. Resilient axis, vulnerable direction

The current results revealed an intact fundamental structure of the axial reference system in HFA. This suggests that previously reported difficulties in non-linguistic spatial tasks in this population did not result from the breakdown in the axial organization in spatial memory or non-linguistic deficits in direction discrimination. We did observe, however, subtle deficits in spatial language, consistent with previous reports suggesting difficulties in this domain (Ohta, 1987; Perkins, Dobbinson, Boucher, Bol, & Bloom, 2006; Vulchanova, Talcott, Vulchanov, & Stankova, 2012; Bochynska, Coventry, Vulchanov, & Vulchanova, 2019). HFA individuals showed higher number of errors in spatial language productions as well as greater proportions of looks to the wrong axis and subsequently, to the opposite direction when processing the meanings of spatial terms.

Crucially, the observed language difficulties mapped on to aspects of the axial structure that was observed in the non-linguistic tasks. Specifically, directional errors that appeared in the HFA group were one of the most frequent errors and were limited almost exclusively to the horizontal axis, i.e. confusions of the terms *left* and *right* (note, however, that although the effects of the axis on memory and language were robust for both TD and HFA groups, the observed effects of direction in the HFA group were weaker and more variable). This pattern resembles the structure of spatial representation that emerged in the non-linguistic tasks and was also observed in previous studies (Hayward & Tarr, 1995; Landau & Hoffman, 2005). That is, direction within the axis is more fragile than axial organization, and directional errors are most frequent within the horizontal axis.

Another frequent error observed in the HFA group, but not in the TD group, was the use of the terms *front* and *back* for the regions above and below the Reference object. These errors could suggest difficulties with the representations of the axis, and not primarily direction, in spatial language in HFA. However, the front/back errors were systematic substitutions rather than axial errors; that is, they were limited only to the vertical axis and never occurred for locations along the horizontal axis. Thus, it would be incorrect to conclude that the HFA group showed deficits in mapping axial terms to the correct axes. Rather, the *front/back* substitutions for the *above/below* terms could point to momentary changes in the interpretation of an ambiguous stimulus layout (e.g. a bird-eye view instead of the first-person-view of the stimulus). Although these substitutions are intriguing and could point to a behavior specific to the HFA population, it is important to note that these confusions resemble similar errors found in younger, typically developing children.

Similarly, more looks among HFA participants to locations along the Different Axis in the language comprehension task could suggest difficulties with linguistic representation of the axes. However, these looks to the Different Axis disappeared by the second half of the trial, suggesting that even though HFA individuals might be less efficient in identifying the correct axis, they successfully do so before identifying the final location that corresponds to the spatial term they have heard. Contrary to that, the HFA group still looked more to the incorrect direction upon identifying the spatial location, a behavior that suggests deficits in direction discrimination that occurs as the spatial term is being interpreted. Overall, this indicates a range of small but selective deficits in spatial language in HFA individuals that revolve around direction discrimination within the horizontal axis.

Finally, we observed directional errors in spatial language production only in the youngest participants with HFA (i.e. children and adolescents but not adults). This suggests that difficulties with directional terms in spatial language might not persist into adulthood in HFA, pointing to delay rather than arrest in the acquisition of projective prepositions in this population.

6.3. From spatial representations to linguistic labels

Finally, overall verbal abilities did not explain group differences observed in spatial language production and comprehension. We expected that difficulties observed in spatial language tasks, which were nevertheless absent in spatial memory tasks, might correlate with verbal abilities in the HFA group. One possibility is that the measures of verbal abilities applied here tap into the aspects of vocabulary that are independent from spatial language abilities, or that this measure is not sensitive enough to identify subtle deficits in this domain. Another possibility is that some aspects of the designs applied here elicited differences in linguistic but not in the non-linguistic tasks, as the results still come from different, although very closely matched, designs.

However, the current findings might also suggest that spatial language difficulties do not result from generally poorer verbal abilities or deficits in the non-linguistic system but arise at the interface of language and spatial representation. Indeed, individuals with ASD, including high-functioning individuals, have been shown to struggle with complex integration of linguistic meanings and with lexical organization (Naigles & Tek, 2017). For example, young children with ASD do not show a typical shape bias (Potrzeba, Fein, & Naigles, 2015; Tek & Naigles, 2017; Tek et al., 2008), an important mechanism that supports learning the meanings of novel words in the first years of life (Landau, Smith, & Jones, 1988). As similar processes might be involved in mapping the meanings of spatial terms onto non-linguistic representations of space, HFA individuals could show weaknesses in integrating the linguistic and non-linguistic aspects in spatial language domain. Consequently, the vulnerable aspects of spatial representations, such as direction discrimination along the horizontal axis, could be compromised in language but not in the non-linguistic system, resulting in more pronounced selective fragility in directional coding in language tasks.

7. Conclusions

The current studies compared the linguistic and non-linguistic representation of spatial locations between HFA and TD individuals. The findings point to a strong axial organization in language and memory in both groups, which was also remarkably visible in participants' gaze behavior. Additionally, the representation of the direction within the axes (left/right, above/below) was more fragile than the representation of the axes (vertical or horizontal), and this characteristic was shared by linguistic and non-linguistic spatial systems in both HFA and TD individuals. Crucially, however, HFA individuals showed subtle deficits in the linguistic encodings of spatial location that were not reflected in their non-linguistic representations of space. For example, despite intact discrimination of direction in memory, the HFA group showed difficulties with direction discrimination in processing the words that represent direction within the axis (especially, *right/left*). This finding points to a degree of autonomy between spatial language and the non-linguistic spatial representation systems that support it. The observed difficulties with directional terms in HFA clearly reflected the structural organization of the non-linguistic system. That is, spatial language errors were mostly restricted to the direction component, which was overall weaker in the non-linguistic representations. In addition, directional errors in language were restricted to the horizontal terms (*left/right*) and direction discrimination in the non-linguistic tasks was also weaker along the horizontal axis. These parallels reflect structural similarities between spatial language and spatial representation. Importantly, these observed difficulties were not accounted for by the overall verbal abilities of HFA individuals, suggesting the presence of a subtle linguistic deficit that standardized measures of language abilities do not detect. Finally, we also observed that the directional errors in language production were restricted to children and adolescents in the HFA group, suggesting that these errors might not persist into adulthood in this population. This points to a developmental delay rather than arrest in the acquisition of directional spatial terms in HFA. The current findings provide significant clinical contributions, as they can inform future language measures in HFA, as well as carry important theoretical implications in the area of language and cognition, showing structural similarities between linguistic and non-linguistic systems along with a degree of autonomy between the systems.

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