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Pitch perception deficits in nonverbal learning disability

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ABSTRACT

The nonverbal learning disability (NLD) is a neurological dysfunction that affects cognitive functions predominantly related to the right hemisphere such as spatial and abstract reasoning. Previous evidence in healthy adults suggests that acoustic pitch (i.e., the relative difference in frequency between sounds) is, under certain conditions, encoded in specific areas of the right hemisphere that also encode the spatial elevation of external objects (e.g., high vs. low position). Taking this evidence into account, we explored the perception of pitch in preadolescents and adolescents with NLD and in a group of healthy participants matched by age, gender, musical knowledge and handedness. Participants performed four speeded tests: a stimulus detection test and three perceptual categorization tests based on colour, spatial position and pitch.

Results revealed that both groups were equally fast at detecting visual targets and categorizing visual stimuli according to their colour. In contrast, the NLD group showed slower responses than the control group when categorizing space (direction of a visual object) and pitch (direction of a change in sound frequency). This pattern of results suggests the presence of a subtle deficit at judging pitch in NLD along with the traditionally-described difficulties in spatial processing.

What does this paper add?

Nonverbal learning disability (NLD) is a complex and multisymptomatic disorder characterized by the presence of deficits in visuospatial processing and in other cognitive abilities such as numerical processing, prosody. However, despite the wide range of cognitive processes affected, auditory perception has been historically discarded as part of the diagnosis criteria for NLD. In the current study, we report a possible deficit in pitch perception in NLD. Our results indicate that children with NLD show significant difficulties at judging the direction of a change in the frequency of sounds. This lower level of pitch perception performance could be associated with structural anomalies previously observed in children with NLD (e.g. white matter alterations in the right hemisphere). The right hemisphere has generally been related to the processing of speech

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prosody. Keeping in mind that the key mechanism to decode speech prosody is based on deciphering the variations in pitch that are available in the speech signal, our results may perhaps explain the difficulties in understanding speech prosody previously found in NLD.

1. Introduction

Nonverbal learning disability (NLD) is a neurological learning disorder mostly related to the right hemisphere (see Semrud-Clikeman & Hynd, 1990) whose prevalence is estimated to be around 5–10% of all learning disabilities (Davis & Broitman, 2011). This disability was first described by Myklebust (1975) as a subtype of learning disorders that affect non-linguistic abilities.

Although researchers in the field do not question the need of a diagnostic label for NLD, there is some disagreement regarding the criteria used in its differential diagnosis. In an attempt to reduce this ambiguity in the diagnosis of NLD, Mammarella and Cornoldi (2014) (see also Fine, Semrud-Clikeman, Bledsoe, & Musielak, 2013) proposed several criteria based on a review of the last 30 years of research in the field NLD is characterized by (1) poor visuospatial and good verbal intelligence, (2) the presence of difficulties in visuoconstructive and fine-motor abilities, (3) poor mathematical and good reading decoding achievement at school, (4) spatial working memory deficits, and (5) emotional and social difficulties. The authors of this comprehensive study also suggested that the first criterion should always be present in the diagnosis of NLD and at least two of the other four criteria should be met.

So far, the visuospatial and mathematical abilities have monopolized most of the research conducted on NLD. In a recent study, Crollen, Vanderclausen, Allaire, Pollaris, and Noël (2015) observed visuospatial and numerical processing deficits in children diagnosed with NLD. More specifically, these authors explored the spatial representation of numbers (see Dehaene, Bossini, & Giroux, 1993) and found that children with NLD were less able to represent numbers spatially than a control group of healthy children. In particular, children with NLD did not show any tendency to associate small numbers to the left side and bigger numbers to the right side of the external space, a phenomenon previously observed in healthy participants and known as the SNARC effect (Spatial Numerical Association of Response Codes; see Dehaene, Bossini, & Giroux, 1993; see also Hubbard, Piazza, Pinel, & Dehaene, 2005, for a review).

Children and adolescents with NLD do not usually show anomalies in basic language skills (e.g. morphology or phonology), reading decoding, or in any other cognitive function such as attention or long-term memory (see Mammarella et al., 2009; Pennington, 2009; Rigau-Ratera, Garcia-Nonell, & Artigas-Pallares, 2004; Rourke & Tsatsanis, 2000). Importantly, previous studies have also discarded the presence of auditory deficits in NLD (see Rourke, 1989, 1995).

Regarding the possible neural bases of NLD, it has been suggested the presence of significant white matter perturbations in the right hemisphere of patients with NLD (Rourke, 1987, 1988, 1995). According to Rourke (1987), white matter alterations in the right hemisphere correlate positively with the presence of symptoms commonly described in NLD such as difficulties in visuospatial processing and speech prosody. Given the prominent participation of the right hemisphere (see Gandour et al., 2004; Ross & Monnot, 2008; Tong et al., 2005; Wong, 2002; for a review) and, specially its posterior (parietal) regions (see Perrone-Bertolotti et al., 2013) in processing prosody of speech, it is not surprising that this linguistic dimension is affected in NLShapiro and Danly (1985) demonstrated, after analysing sentences read by patients with lesions in different areas of the brain, that only patients with post-Rolandic posterior lesions in the right hemisphere produce altered prosodic speech characterized with exaggerated variations in pitch. More recently, in a study conducted with sleeping 3-month-old infants, Homae, Watanabe, Nakano, Asakawa, and Taga (2006) showed that the right temporoparietal regions of the brain are, that the right temporoparietal regions of the brain are more sensitive to normal speech – which includes variations in pitch and loudness- than its left counterparts (see also Arimitsu et al., 2011).

Noteworthy, the key mechanism to decode speech prosody is based on decoding variations in pitch; that is, on discriminating dynamic changes in the frequency of sound (see D. Patel, Peretz, Tramo, & Labreque, 1998). Interestingly, patients with a unilateral cerebrovascular lesion in the right hemisphere show poorer perception of pitch contour than patients with the same lesion in the left hemisphere (see Peretz, 1990). Despite the involvement of pitch perception in the comprehension of speech prosody, and the fact that the right hemisphere contributes to both processes, there are no studies specifically exploring possible deficits in pitch perception in patients with NLD.

Another reason for investigating pitch perception in NLD is based on previous behavioural evidence suggesting that, in a similar way as in the already mentioned SNARC effect, high and low sound frequencies seem to be mapped onto high and low spatial positions, respectively. In fact, there is strong evidence suggesting that the processing of pitch and vertical coordinates in space influence each other in such a way that the responses to one of these dimensions can be modified by manipulating the other (see Melara & O'Brien, 1987; Occelli, Spence, & Zampini, 2009; Rusconi, Kwan, Giordano, Umilta, & Butterworth, 2006). Crucially for the present study, Melara and O'Brien (1987) demonstrated the existence of a crossmodal link between pitch and spatial elevation. In their study, participants had to make an auditory or visual classification task while ignoring any stimulus variation in the other (irrelevant) dimension. When pitch was the relevant dimension, the participants had to press one of two different buttons every time they perceived a high or a low frequency sound. The auditory stimuli were presented together with a dot that could appear in a higher or lower position with respect of the central point of fixation. When the spatial position was the relevant dimension, the same procedure was used but the participants had to respond to the position of the dot instead of responding to sound pitch. These authors observed that a variation in the auditory dimension affected the participants' responses to the visuospatial dimension and vice versa. Moreover, the results revealed faster responses in the compatible trials, in both auditory and visual conditions (e.g. the dot appeared in a high position while a high frequency sound was presented).

The presence of a strong crossmodal association between the pitch and verticality has also been observed in many studies using a large variety of experimental methodologies (see Occelli et al., 2009; Parise & Spence, 2009; Sonnadara et al., 2009; see Deroy & Spence, 2013; Deroy, Fernández-Prieto, Navarra & Spence, in press; Spence, 2011 for reviews), including indirect tasks in which the participants were not asked to perform any judgment regarding pitch or spatial elevation (Lidji, Kolinsky, Lochy, & Morais, 2007; Rusconi et al., 2006). Perceiving sounds with high or low frequencies can even bias the perceivers' visuospatial attention towards upper or lower spatial locations, respectively (see Chiou & Rich, 2012; Mossbridge, Grabowecky, & Suzuki, 2011).

In the current study, we explored auditory pitch and visuospatial perception in a group of adolescents with NLD (NLD group) and in a control group of adolescents without any neurological or psychiatric disorder. To achieve this goal, four computer-based tests were designed:

1 *Auditory pitch categorization test*. This test was designed to obtain accurate measures (reaction times, RTs; and accuracy) of the participants' ability to categorize sounds containing either an ascending or a descending change in pitch.
2 *Visuospatial categorization test*. This test was created as an analogy of the auditory pitch categorization test. The participants' task consisted on judging the direction, along the vertical axis, of a visual stimulus (a filled circle).
3 *Speeded stimulus detection test*. This test was included in our study to obtain an index of the participants' speed at responding to external stimulation. This was done to ensure that the NLD group was not generally slower in responding to external stimulation than the control group.
4 *Colour categorization test*. This test was included to address the participants' ability to use sensory information and categorize stimuli according to a specific perceptual dimension (in this case, colour).

While no difference was expected between the two groups in the last two tests (speeded detection and colour categorization), we expected to observe poorer performance in the NLD group than in the control group in the first two tests (involving pitch and visuospatial judgments, respectively). Finally, according to our specific hypothesis that pitch processing would be impaired in NLD, a correlation between the measures obtained in the first two tests was also expected.

2. Method

2.1. Participants

Eight male adolescents with NLD (six right handed, *mean* age 13.3 ±*SD* 1.5 years) and eight healthy male adolescents (six right handed, *mean* age 13.4 ±*SD* 1.6 years) participated in the study. The patients with NLD were matched by age and handedness, and were recruited at the Learning Disorders Unit (Unitat de Trastorns de l'Aprenentatge Escolar, UTAE) of Hospital Sant Joan de Déu (Barcelona, Spain). The patients had already been diagnosed with NLD and were selected according to the following criteria (see Fine, Semrud-Clikeman, Bledsoe, & Musielak, 2013):

- Presence of difficulties in motor abilities (fulfilling the DSM-IV-TR criteria for developmental coordination disorder) as measured in Purdue Pegboard Test (manual dexterity and bimanual coordination). Scores had to be lower than typically developing children by 15 points (1 < SD).

- Visuospatial and visuomotor difficulties, with scores lower than typically developing children by 15 points (1 < SD) in the NEPSY Arrows subtest and the Blocks Design subtest from the Wechsler Intelligence Scale for Children IV (WISC-IV).

- The presence of at least 2 of the following symptoms:

- Social difficulties (assessed using the Vineland Adaptive Behavior Scale, VABS). Scores had to be 15 points below typically developing children (1 < SD) in communication, living skills and socialization subtests.
- Verbal IQ higher by 15 points or more than typically developing children (1<SD) in the similarity, vocabulary and comprehension subtests of WISC-IV.
- Mathematical disability as observed in scores lower than typically developing children by 15 points (1<SD) in the mathematical subtests from WISC-IV.

- Exclusion criteria were the presence of intellectual disability in WISC-IV, the presence of specific learning disorder with reading or written expression impairments (according to Diagnostic and statistical manual of mental disorders, 5th ed., DSM-5), the presence of academic difficulties in linguistic skills, attention deficit/hyperactivity disorder (as assessed by the Conners scales for parents, CPRS-48, and teachers, CTRS-28) and/or autism spectrum disorder (as evaluated by the Autism Diagnostic Interview-Revised, ADI-R).

2.2. Apparatus

An Intel Core computer and a 15-inch CRT monitor (Philips 107-E Monitor, 85 Hz) were used to run the four tests. The experimental procedure was controlled by E-Prime 2.0 (Psychology Software Tools Inc., Pittsburg, PA). The study was

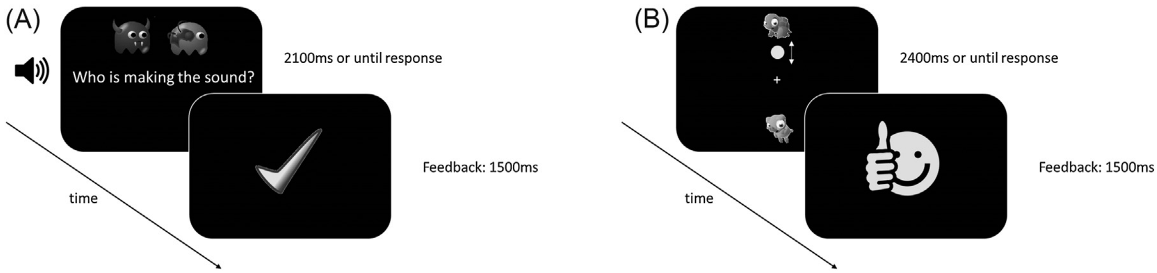

Fig. 1. (A) Example of an experimental trial in the Auditory Pitch Categorization Test. The sound played could be four different frequency sweeps; two ascending and two descending (10% of trials the sound did not change). Participants could receive three different feedbacks after the response: positive (correct response), negative (incorrect response) or warning signal (omission or no response). (B) Example of an experimental trial in the Visuospatial Categorization Test. The circle appeared above or below the fixation point, and could move up or down (10% of trials the circle did not move). Participants could receive three different feedbacks after the response: positive (correct response), negative (incorrect response) or warning signal (omission or no response).

conducted in a dimly-lit and sound-attenuated room. The participants sat at an approximate distance of 60 cm from the monitor. Two loudspeakers (Phillips A 1.2 Fun Power, China) were located at each side of the computer screen.

2.3. Experimental tasks

All of the participants performed the four computerized tests. Their performance was measured in terms of reaction times (RTs) in correct responses and accuracy (the proportion of incorrect responses in each test). These were considered as the dependant variables in all of the statistical analyses.

2.3.1. Auditory pitch categorization test

This test was divided in two blocks, with a one-min pause between them. Each block included 44 test trials. The participants had to identify the direction (ascending or descending) of a progressive change in the sound frequency of pure tones. There were four different frequency sweeps with a duration of 2100 ms; two ascending (with a the frequency ranging from 466 Hz to 587 Hz, and from 932 Hz to 1174 Hz) and two descending (from 466 Hz to 370 Hz, and 932 Hz to 739 Hz). Before the test, the participants were told that the two directions in frequency (ascending or descending) were produced by two different cartoon characters (e.g., the green cartoon character produced ascending sweeps and the red character produced descending sweeps; see Fig. 1A) and that their task consisted on deciding which of the two characters produced the tone in each trial. This association between the cartoons and the tones was counterbalanced across participants. During the main pitch categorization test, participants responded with two different keys of the computer keyboard to indicate the character that produced the tone just presented (e.g., "a" for the green cartoon 1 and "l" for the red cartoon 2). Visual feedback (indicating a correct or an incorrect response or a response omission) was provided, during 1500 ms, after each response, or after 2400 ms in case of no response. The participants were also instructed to avoid responding when the tone did not change, which occurred in ten percent of the trials. These 'catch' trials were introduced to ensure that participants paid attention to the sounds.

2.3.2. Visuospatial categorization test

The test was divided in two blocks, each one including 77 trials, and also included a one-minute pause between the blocks. The participants had to judge whether a circle (1.5 cm of diameter and located 3 cm above or below of the fixation point) was moving towards a cartoon image of a turtle (located at the top of the screen; 6 cm above a centrally-presented fixation point), or a cartoon image of a pig (located at the bottom of the screen; 6 cm below the fixation point). Each trial started with the appearance of a fixation white cross (2 cm x 2 cm) in the middle of the screen, on a black background. The circle always appeared slightly above or below the fixation point, and moved up or down in the vertical axis until the participant's response or up to 2400 ms in case of no response. As in the previous test, participants were instructed to press the "a" or "l" keys using the index finger of their left and right hand, respectively. Each of these two keys was associated to one of the cartoons and this association was counterbalanced across participants. In order to ensure that the participants were attending to the visual stimuli, they were encouraged to avoid responding in catch trials where the circle did not move, which represented the 10% of the total amount of trials. As in the previous test, visual feedback was provided for 1500 ms after each participant's response or after 2400 ms if no response was registered (see Fig. 1B).

2.3.3. Speeded stimulus detection test

In 60 different trials, participants had to detect a yellow circle (diameter: 3 cm) and press the keyboard's space bar as quickly as possible with their dominant hand. Each trial started with the appearance of a fixation white cross (2 cm x 2 cm) in the middle of the screen, on a black background. The white cross remained on the screen for a period randomly chosen from the following time intervals: 600, 800, 1000, 1200, 1400 or 1600 milliseconds. After this period, a yellow circle (diameter:

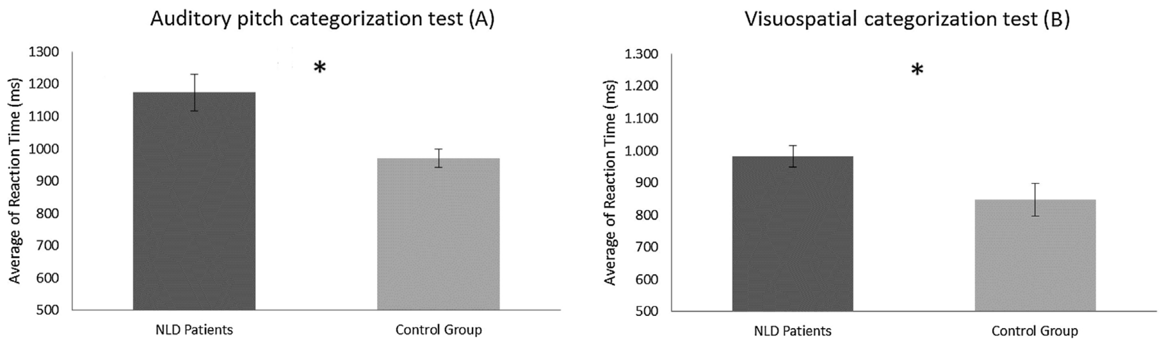

Fig. 2. Average of Reaction Times (in milliseconds) in the two tests used in the study to measure visuospatial and pitch processing. (A) Average of RTs in the Visuospatial Categorization Test in NLD Patients and in the Control group. (B) Average of RTs in the Auditory Pitch Categorization Test in NLD Patients and in the Control group. Error bars show standard errors. Asterisks show significant differences between groups.

Table 1
Percentage of errors and standard deviations of the NLD and the Control group in the four computerized tests.

		Categorization errors	Omission errors	False alarms (catch trials)[a]
Auditory pitch categorization test	NLD Group	17.5% (SD = 11.28%)	12.34% (SD = 6.56%)	56.28% (SD = 34.72%)
	Control Group	5.78% (SD = 4.32%)	0.78% (SD = 0.65%)	10.94% (SD = 12.39%)
Visuospatial categorization test	NLD Group	3.68% (SD = 3.11%)	0.37% (SD = 0.68%)	3.46% (SD = 5.32%)
	Control Group	5.29% (SD = 4.21%)	0.45% (SD = 0.37%)	10.56% (SD = 7.73%)
Speeded stimulus detection test	NLD Group		8.33% (SD = 2.95%)	
	Control Group		7.70% (SD = 4.27%)	
Colour categorization test	NLD Group	13.95% (SD = 5.19%)	5.63% (SD = 2.66%)	
	Control Group	13.96% (SD = 5.84%)	7.29% (SD = 3.56%)	

[a] The percentage of false alarms was calculated based on catch trials where participants had to avoid responding (10% of the total amount of total trials).

3 cm) was presented on the centre of the computer screen until the participant's response or for 3000 ms, in case of no response.

2.3.4. Colour categorization test

The participant had to judge the colour of a circle (diameter: 3 cm) as fast and accurately as possible in 60 different trials. The procedure was identical to the previous test with the following exceptions: the colour of the circle could be either blue or yellow, and the task consisted on pressing the "a" or "l" keys as quickly as possible using the index finger of their left and right hand, respectively, to indicate the colour of the ball (i.e., blue or yellow). The association between the response keys and the colours was counterbalanced across participants.

3. Results

Considering the small size of the sample of participants, a non-parametric statistical approach was adopted to analyse the data obtained in all of the four tests included in the study. It is worth highlighting that using cognitive computer-based methods allows us to obtain reliable (and generalizable) data even in small sample sizes such as the one included in the current study. This is so because of (1) the capability of computerized tasks to deliver highly-accurate measures (e.g., at the level of milliseconds) of cognitive functions, and (2) the fact that the measures that are obtained in these kind of tasks are based on sensory-driven speeded judgments, rather than based on other perhaps more subjective decisions. Another key factor that increases statistical power, both in the present and in many previous studies, is the fact that the participants' measures are also obtained from an average of many different data points (e.g., 154 trials, in one particular test).

3.1. Auditory pitch categorization test

The NLD and the control group were compared in terms of RTs from trials with a correct responses, omission errors (i.e., not responding), categorization errors (i.e., choosing the wrong cartoon character), and false alarms in catch trials (i.e., pressing a key instead of inhibiting response for tones without pitch change). A non-parametric Mann–Whitney *U* test conducted with RT data revealed slower responses in the NLD group than in the control group ($U = -3.151$, $p = 0.001$; see Fig. 2A). The NLD group also showed a significantly lower percentage of correct responses than the control group ($U = 3.002$, $p = 0.001$). Further analyses on error responses revealed poorer performance in the NLD group compared to the control group in all of the 3 types of error (categorization: $U = 0.268$ $p = 0.021$; false alarms: $U = -2.409$, $p = 0.015$; and omissions: $U = -3.424$, $p < 0.001$) (Table 1).

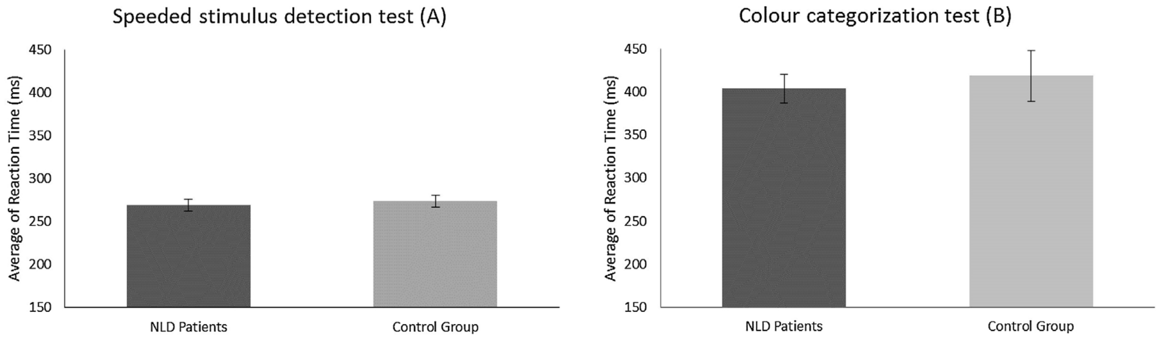

Fig. 3. Average of Reaction Times (in milliseconds) in the two control tests used in the study to assess participants' speed at responding to external stimulation: (A) Average of RTs in the Speeded Detection Test in the group of adolescents with NLD and in the Control group. (B) Average of RTs in the Colour Categorization Test in the NLD Patients and in the Control group. Error bars show standard errors. Asterisks show significant differences between groups.

3.2. Visuospatial categorization test

The NLD and the control group were compared in terms of RTs from trials with a correct response, omission errors, categorization errors (i.e., choosing the wrong direction) and false alarms in catch trials (where participants had to avoid responding). A non-parametric *U* Mann-Whitney analysis revealed that NLD group's responses at judging the circle movement direction of the circle were significantly slower than the control group ($U = -2.100$, $p = 0.038$; see Fig. 2B). No significant differences were found between the two groups in terms of correct responses percentage ($U = -0.686$, $p = 0.505$), the percentage of categorization or omission errors (categorization: $U = -0.527$, $p = 0.645$; and omissions: $U = -0.817$, $p = 0.051$). The control group showed a significantly higher percentage of false alarms in catch trials than the group of adolescents with NLD ($U = -2.014$, $p = 0.05$) (see Table 1).

3.3. Speeded stimulus detection test

Reaction times, obtained from trials with a correct response, and omission errors (i.e., not responding after the appearance of the visual target) were used to compare the performance in the two groups (NLD and control participants). A non-parametric Mann-Whitney *U* test revealed equivalent RTs in both groups ($U = 9.522$, $p = 1$) (see Fig. 3A). No significant differences were observed in terms of omission errors between groups ($U = -0.214$, $p = 0.878$; see Table 1).

3.4. Colour categorization test

The NLD and the control group were compared in terms of RTs in trial with a correct response, omission errors and categorization errors (i.e., choosing the wrong colour). A non-parametric Mann-Whitney *U* showed no difference in RTs between the two groups ($U = -0.105$, $p = 0.959$) (see Fig. 3B). No difference was found between the two groups in terms of omission or categorization errors ($U = -0.691$, $p = 0.505$; $U = 0.643$, $p = 0.574$; respectively) (see Table 1).

3.5. Correlation between visuospatial and pitch categorization

The non-parametric Spearman's correlation test was used to evaluate the possible relationship between the participants' performance in the principal measures of the present study, mainly the ones obtained in the visuospatial categorization test and the auditory pitch categorization test; including RTs and errors (i.e., omissions, false alarms and categorization errors). Considering data from the whole sample (NLD patients and the Control group), a significant correlation was found between the RTs in these two tests ($R = 0.679$, $p = 0.004$). Participants that were slower at categorizing pitch were also slower at categorizing the direction of a movement. However, no correlation was found between the two tests in any type of error (omission: $R = -0.117$, $p = 0.667$; false alarms: $R = -0.082$, $p = 0.762$ and categorization error: $R = 0.006$, $p = 0.983$).

4. Discussion

Taken together, our results indicate that both the NLD and the control group performed equivalently in a simple stimulus detection test and a colour categorization test. This pattern of results suggests that the participants with NLD did not show general slowness or poorer processing (i.e., leading to an increase of errors) when responding to external stimulation. Importantly, the participants included in this group were able to categorize stimuli according to a non-spatial dimension (i.e., colour). In contrast, the results of the visuospatial test confirmed our hypotheses: The NLD participants were slower at responding to the direction of a visual object's movement. Crucially, the results obtained in the pitch categorization test indicate that the participants with NLD also had a poorer performance (observed both in RTs and in the percentage of number of errors) at judging the direction of a dynamic change in auditory pitch (ascending vs. descending). Finally, a positive correlation was found, in the participants' RTs, between the results obtained in the visuospatial categorization and the auditory pitch categorization test.

Despite the fact that the computerized tasks provided us with statistically reliable data, a limitation of the present study is the small sample tested. We tried to compensate this restriction with (1) a strict match between the two groups (in terms of age, gender, handedness and musical knowledge), (2) the use of non-parametric analyses, and, perhaps more importantly, (3) the use of highly-accurate computerized measures of cognitive functions based on many data points. Another possible limitation of the study is the difficulty of obtaining a differential diagnosis of NLD. Although the participants in the current study were carefully selected among a larger sample of NLD patients (that included children with comorbidities) and did not meet the criteria for specific learning disorder with impairment in reading and/or with impairment in written expression (see Diagnostic and statistical manual of mental disorders, 5th ed., DSM-5), we cannot rule out, in absence of a closer examination of language skills, that they did not show any linguistic difficulty that remained undetected during their clinical assessment at our centre. Further testing, perhaps including a larger sample of participants with NLD, will be needed to elucidate whether the subtle deficits at judging pitch observed in the present study correlate with specific linguistic abilities involving the adequate processing of variations in sound frequency (e.g., prosody and intonation; see Rourke, 1995).

Children and adolescents with specific language impairment (SLI) often show difficulties in other cognitive areas such as visuomotor abilities (Hill, 2001), social skills (Beitchman et al., 1996) and/or mathematics (Mainela-Arnold, Alibali, Ryan, & Evans, 2011). Previous studies have even associated SLI with an abnormal development of brain structures underlying the procedural memory system (affecting learning, motor and other cognitive skills; see Ullman & Pierpont, 2005). Despite of the relative overlap between SLI and NLD in terms of specific symptoms such as motor and abstract reasoning skills, it is worth highlighting that the NLD patients that participated in the present study did not show any obvious difficulty in language (as observed both at school and during the psychological and psychiatric assessment conducted at our centre) and had normal verbal intelligence (see Fine, Semrud-Clikeman, Bledsoe, & Musielak, 2013).

To our knowledge, there is no previous evidence suggesting the presence of basic auditory deficits at the level pitch categorization in NDL. In our opinion, although the children with NLD can present short-term memory impairments when they need to bind information from different categories (e.g. shape and colour), these difficulties seem to appear in more complex tasks including a large number of combinations. In a study conducted by Garcia, Mammarella, Pancera, Galera, and Cornoldi (2015), children with NLD showed poorer performance than a control group in memory for shape-colour bindings, the task had a total of 72 combinations (8 shapes and 9 colours). In stark contrast with this previous work, our much easier auditory categorization task had only two possible combinations (e.g. each of two cartoon characters combined with two possible sounds), imposing much less short-term memory demands to the participants.

Non-verbal learning disorder has mainly been characterized, among other aspects, by the presence of difficulties in spatial and abstract tasks (Crollen et al., 2015; Fine, 2012; Rourke, 1995). Our results support and complement this previous evidence by revealing the presence of anomalies in spatial-driven judgments regarding the direction of a visual object's movement. Our results also extend previous evidence reflecting perceptual and cognitive anomalies in NLD to the much less studied case of auditory perception, where difficulties in judging pitch have been found. Due to their difficulties to decode speech prosody (see Rourke, 1989), NLD patients are less able to produce and understand language intonation, thus having difficulties to grasp the difference between statements, commands, questions, etc. (see Rourke, 1995). An adequate processing of pitch variations in speech is essential to understand the others' messages (see Patel et al., 1998). At a speculative level, the difficulties in understanding speech prosody previously reported in the literature may easily be attributed to a deficit at the level of pitch representation. Regarding the possible neural basis of perceptual anomalies reported in the present study, several studies conducted in adults revealed the principal involvement of the right hemisphere in the processing of speech prosody (i.e., processing the pitch and loudness contour in speech signals) (see Gandour et al., 2004; Tong et al., 2005). This is particularly true for posterior (parietal) regions of this hemisphere (see Perrone-Bertolotti et al., 2013). Therefore, our study, together with previous evidence suggesting the presence of structural anomalies in the right hemisphere in children with NLD (Rourke, 1988) and the involvement of this hemisphere in the processing of speech prosody (see ; Shapiro and Danly; 1985; Homae et al., 2006; Arimitsu et al., 2011) may perhaps indicate that deficits found in the perception of prosody may be the consequence of a more basic deficit in perceiving pitch. Previous neuroimaging studies conducted in healthy adults suggest that detection of subtle pitch variations embedded in a melody significantly activates the intraparietal sulcus (IPS) (Foster & Zatorre, 2010a, 2010b), an area considered to be involved in spatial-based tasks. If some specific pitch-based tasks are linked with spatial processing (see Foster & Zatorre, 2010a, 2010b), it seems plausible that a structural and/or functional impairment of these brain areas of the right hemisphere (as it is reported in NLD patients; see Rourke, 1988) may affect both, pitch and visuospatial processing.

According to Rourke (1988) and his "*white matter*" account of NLD, this pathology could be the result of white matter abnormalities in the right hemisphere. However, further research is needed, perhaps using functional magnetic resonance (fMRI), to relate the auditory and visuospatial deficits found in the present study to possible dysfunctional areas of the brain. The visuospatial and the pitch categorization tasks were, in the current study, designed to avoid the use of language with spatial connotations. Labels such as "*arriba*" (up), "*abajo*" (down), "*alto*" (high), or "*bajo*" (low) were avoided both in the instructions given to participants and during the test sessions. Participants were instructed to respond to a cartoon associated to the response (e.g., the ascending sound was produced by the monster A and descending sound by the monster

B). Furthermore, participants of the current study were Spanish and Catalan speakers, and neither of these two languages use spatial terms in their most frequent words to describe pitch ("agudo", in Spanish, and "agut", in Catalan, for high-pitched sounds and "grave", in Spanish, and "greu", in Catalan, for low-pitched sounds). So far, the possible role of language labelling in the experimental demonstrations of crossmodal correspondences between space and pitch has been controversial (see Spence, 2011; for a review), especially when taking into account the strong evidence suggesting that these correspondences occur even in prelinguistic infants (Dolscheid, Hunnius, Casasanto, & Majid, 2014; Walker et al., 2010).

In summary, our results show, in line with previous studies, that children with NLD present difficulties in a visuospatial task. This is, according to previous literature, the core of the cognitive deficits that characterize this neurological disorder. In addition, and more importantly, our study also revealed a slower and poorer performance in a pitch-based auditory task in these patients. This difficulty in categorizing an auditory change in frequency could be associated with structural anomalies previously observed in NLD. More research is needed to clarify this possible association. The deficit in pitch processing could perhaps underlie other difficulties in other cognitive areas (e.g., understanding and producing speech prosody in face-to-face interaction) already found in patients with NLD. Therefore, our results could open new paths in the diagnosis and treatment of this cognitive disability.

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