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**Do Developmental Dyslexia and Congenital Amusia Share Underlying Impairments?**

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Data and material for this study are available at: [https://osf.io/grua5/?view\\_only=acf1fc30c6c546bab47bbd44c192cfdc](https://osf.io/grua5/?view_only=acf1fc30c6c546bab47bbd44c192cfdc)

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**Abstract**

Developmental dyslexia and congenital amusia have common characteristics. Yet, their possible association in some individuals has been addressed only scarcely. Recently, two converging studies reported a sizeable comorbidity rate between these two neurodevelopmental disorders (Couvignou et al., *Cognitive Neuropsychology* 2019; Couvignou & Kolinsky, *Neuropsychologia* 2021). However, the reason for their association remains unclear. Here, we investigate the hypothesis of shared underlying impairments between dyslexia and amusia. Fifteen dyslexic children with amusia (DYS+A), 15 dyslexic children without amusia (DYS-A), and two groups of 25 typically developing children matched on either chronological age (CA) or reading level (RL) were assessed with a behavioral battery aiming to investigate phonological and pitch processing capacities at auditory memory, perceptual awareness, and attentional levels. Overall, our results suggest that poor auditory serial-order memory increases susceptibility to comorbidity between dyslexia and amusia and may play a role in the development of the comorbid phenotype. In contrast, the impairments observed in the **DYS+A** children for auditory item memory, perceptual awareness, and attention might be a consequence of their reduced reading experience combined with weaker musical skills. Comparing **DYS+A** and **DYS-A** children suggests that the latter are more resourceful and/or have more effective compensatory strategies, or that their phenotype results from a different developmental trajectory. We will discuss the relevance of these findings for delving into the aetiology of these two developmental disorders and address their implications for future research and practice.

*Keywords:* developmental dyslexia, tone deafness, auditory short-term memory, auditory perceptual awareness, auditory attention

**Word count:** 23 593.

## SHARED IMPAIRMENTS IN DYSLEXIA AND AMUSIA?

1           Developmental dyslexia is a neurodevelopmental disorder that manifests as a severe and  
2 persistent difficulty in acquiring reading despite otherwise normal intellectual functioning, no  
3 obvious sensory or neurological damage, and adequate educational opportunities (World Health  
4 Organization, 2011). There is strong converging evidence suggesting that developmental  
5 dyslexia results from a specific impairment of phonological processes (Ramus, 2003; Vellutino  
6 et al., 2004), which impedes efficient mapping of phonemic and graphemic representations.  
7 However, the hypothesis that the phonological deficit is the only core impairment in  
8 developmental dyslexia has been challenged by the substantial phenotypic variability of the  
9 dyslexic population (Valdois et al., 2004), and there is still some debate about the potential role  
10 of more primary auditory impairments or temporal processing impairments in the development  
11 of this disorder (Goswami, 2015; Habib, 2021; Hornickel & Kraus, 2013; Lallier et al., 2018).  
12 More generally, the hypothesis that developmental dyslexia as well as other developmental  
13 disorders reflect a core, single underlying cognitive impairment, has been questioned  
14 (Pennington, 2006). Rather than reflecting a single underlying cognitive impairment, they may  
15 be dimensionalities of comorbid features (e.g., Astle & Fletcher-Watson, 2020; Lervåg, 2021;  
16 Pennington, 2006). As for other developmental disorders, dyslexia is frequently comorbid with  
17 other disorders such as developmental language disorder, dyspraxia, dyscalculia, or attention  
18 deficit / hyperactivity disorders (Germanò et al., 2010; Kaplan et al., 1998; McArthur et al.,  
19 2000; Wilson et al., 2015), and it is difficult for a single cognitive deficit model to account for  
20 such comorbidity. This is particularly the case with *heterotypic comorbidity*, namely  
21 comorbidity between disorders from different diagnostic groupings, such as dyslexia and  
22 attention deficit / hyperactivity disorders (Pennington, 2006). In this respect, the extent to which  
23 dyslexia might co-occur with congenital amusia is worthy of study but has so far received little  
24 attention.

## SHARED IMPAIRMENTS IN DYSLEXIA AND AMUSIA?

1           Congenital amusia, or *tone deafness*, refers to a lifelong musical disorder linked to pitch-  
2 processing impairments (Peretz, 2013; Tillmann et al., 2015; Williamson & Stewart, 2013),  
3 occurring despite intact sensory and intellectual functioning and an adequate musical  
4 environment. Individuals with amusia typically fail to recognize familiar tunes without lyrics,  
5 to detect false notes, or to judge whether someone is singing out of tune, including themselves  
6 (Ayotte et al., 2002; Peretz & Hyde, 2003). Just like dyslexia, amusia is suggested to be  
7 genetically influenced (e.g., Fisher & DeFries, 2002 for dyslexia; Peretz et al., 2007; Peretz &  
8 Vuvan, 2017 for amusia) and has been proposed to stem from impaired neuronal migration  
9 (Galaburda et al., 1985; Galaburda & Kemper, 1979 for dyslexia; Hyde et al., 2007 for amusia).  
10 Other intriguing features shared between amusia and dyslexia is that impaired short-term  
11 memory processes and/or impaired conscious access to the relevant representations have been  
12 reported for both disorders (Loui et al., 2011; Moreau et al., 2013; Peretz et al., 2009; Ramus  
13 & Ahissar, 2012; Ramus & Szenkovits, 2008; Tillmann, Levêque et al., 2016). Whereas the  
14 most common interpretation of the specific difficulties observed in dyslexia and amusia  
15 proposes that their phonological/pitch representations are degraded in some way (i.e., are less  
16 precise, underspecified, less categorical, or noisier; e.g., Adlard & Hazan, 1998; Hornickel &  
17 Kraus, 2013; Hyde & Peretz, 2004; Manis et al., 1997; Serniclaes et al., 2004; Ziegler et al.,  
18 2009), new theories (e.g., Boets, 2014; Boets et al., 2013; Peretz, 2016; Ramus & Szenkovits,  
19 2008; Tillmann, Levêque et al., 2016) propose alternative hypotheses, according to which their  
20 representations would in fact be intact, but more difficult to integrate into memory and/or to  
21 access consciously. These memory and awareness impairments have been associated, in both  
22 disorders respectively, with a reduced fronto-temporal connectivity between the auditory cortex  
23 and inferior frontal regions (Albouy et al., 2015, 2019a; Boets et al., 2013; Hyde et al., 2011;  
24 Jasmin et al., 2020; Kovelman et al., 2012; Ramus, 2014). In sum, these various points of  
25 similarity call for a comparative examination of the two disorders.

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1 Initial observations in large samples of adult participants reported no particular  
2 association between amusia and other learning disorders, such as dyslexia (Peretz et al., 2008;  
3 Peretz & Vuvan, 2017). Their main limitation, though, is that the presence of dyslexia was  
4 estimated based on self-report only (i.e., consulting a speech therapist), namely without an  
5 objective measure of literacy performance. This might induce various biases, related in  
6 particular to the age of the participants (dyslexia being nowadays more systematically detected  
7 by the school system) and lack of diagnostic accuracy. Consistent with this view, Peretz et al.  
8 (2008) already noted that younger amusic participants reported learning difficulties (e.g.,  
9 dyslexia) more frequently than their control participants, in contrast to the older participants in  
10 the two groups. Recently, two converging studies using rigorous diagnostic criteria and a large  
11 panel of behavioral measures reported a sizeable comorbidity rate between dyslexia and amusia.  
12 Although dyslexia and amusia are estimated to occur in 3-7% and 1.5-4% of the general  
13 population, respectively (Lindgren et al., 1985; Peretz & Vuvan, 2017), 25-30% of adults with  
14 either dyslexia or amusia also met criteria for the other disorder (Couvignou et al., 2019).  
15 Further investigations conducted at an earlier stage of development (7-12 years of age)  
16 confirmed this observation, with about 34% of the tested dyslexic children diagnosed with  
17 congenital amusia (Couvignou & Kolinsky, 2021). These individuals combined the  
18 characteristics of both disorders, namely slow and erroneous reading and poor phonological  
19 abilities (in particular, poor phonological awareness), as well as difficulties in detecting pitch  
20 changes in melodies despite no history of hearing loss, normal nonverbal IQ and regular  
21 exposure to music.

22 Among the potential explanations for this association (together with the hypotheses of  
23 a common genetic risk factor and of a causal relationship between musical and phonological  
24 impairments, see detailed discussion in Couvignou et al., 2019, 2021), one attractive hypothesis  
25 is that dyslexia and amusia would be different manifestations of the same underlying

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1 impairment(s) that may be expressed in either the language or music domain, which would  
2 increase the likelihood that they occur together in the same individual. As argued by Couvignou  
3 et al. (2019), it seems unlikely that one basic auditory impairment underlies this comorbidity,  
4 because the specific types of auditory impairment usually postulated in dyslexia (such as rapid  
5 temporal processing, amplitude rise time processing, or speech perception in noise, e.g., Farmer  
6 & Klein, 1995; Goswami, 2015; Ziegler, Pech-Georgel, George, et al., 2009) are distinct from  
7 the pitch processing impairment postulated in amusia (Tillmann et al., 2015). Rather, the shared  
8 impairment(s) might be situated at higher processing level(s), which will be the focus of the  
9 present investigation.

10 In addition, as exposed above, it seems hardly plausible that a single common  
11 underlying cognitive impairment accounts for comorbidity. In the present study, we rather  
12 adopted a multifactorial view (e.g., Pennington, 2006) by focusing on three specific cognitive  
13 functions that may be impaired in both dyslexic and amusic individuals: auditory short-term  
14 memory, perceptual awareness, and attention. Without ruling out the importance of other  
15 dimensions that have received increasing interest in recent years in the search for common  
16 underlying impairment(s), such as rhythmic processing, and more generally, the processing of  
17 the temporal structure of sound and/or sequencing (Boll-Avetisyan et al., 2020; Caccia &  
18 Lorusso, 2021; Chang et al., 2019; Fiveash et al., 2021; Lagrois & Peretz, 2019), we will expose  
19 why we think these three cognitive functions deserve further consideration in the aetiology of  
20 both developmental dyslexia and congenital amusia.

21 First, the comorbidity might reflect an inability to integrate phonological or pitch  
22 information into *short-term memory* (STM). STM allows for the temporary storage of  
23 information and is fundamental to making sense of auditory inputs as they unfold over time. In  
24 this respect, STM might act as a bottleneck for learning: poor STM skills may lead to learning  
25 difficulties, particularly with regard to literacy acquisition (Jeffries & Everatt, 2004; Moll et

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1 al., 2016; Schuchardt et al., 2008). Note, however, that the reverse causal relationship must also  
2 be considered as learning likely leads to reciprocal improvements in STM skills (Demoulin &  
3 Kolinsky, 2016; Kolinsky et al., 2020). Verbal STM skills, as measured by digit span or  
4 pseudoword repetition, are typically impaired in children with phonological dyslexia (e.g.,  
5 Kramer et al., 2000; Melby-Lervåg & Lervåg, 2012; Plaza et al., 2002). These impairments  
6 persist into adulthood and have even been observed in trained musicians with dyslexia in both  
7 the verbal and musical modalities (Weiss et al., 2014). In recent years, the memory for serial  
8 order or serial positions of items, which is a particular aspect of STM, has gained growing  
9 interests. Dissociations between preserved item and impaired serial order memory have been  
10 reported in dyslexia (for a review, see Majerus & Cowan, 2016; but see also Staels & Van den  
11 Broeck, 2014, 2015), and the serial order impairment appears to occur for the retention of both  
12 verbal and nonverbal sequence information (Cowan et al., 2017; Hachmann et al., 2014). In  
13 amusia, recent theories have proposed an impairment in pitch STM as the main underlying  
14 cognitive cause of the observed musical difficulties (Tillmann, Levêque et al., 2016). Indeed,  
15 whereas some amusic individuals have normal pitch discrimination thresholds, all amusic  
16 individuals show impaired STM for pitch (Albouy, Mattout, et al., 2013; Albouy, Schulze, et  
17 al., 2013; Foxton, 2004; Tillmann et al., 2009). These impairments have been described at each  
18 level of processing in STM tasks (i.e., encoding, storage, and retrieval of the pitch information),  
19 and have been related to altered brain responses and decreased connectivity within the right  
20 fronto-temporal pathway. In contrast, verbal STM skills of adult amusic individuals seem  
21 preserved, as evidenced by normal performance on forward/backward span tasks or serial word  
22 recognition task (Albouy, Mattout, et al., 2013; Tillmann et al., 2009; Williamson & Stewart,  
23 2010) and brain activations similar to those of controls for the maintenance of words in STM  
24 (preserved activation in the left inferior frontal gyrus and left fronto-temporal connectivity;  
25 Albouy et al., 2019). Nevertheless, the question of whether auditory STM is a unitary construct



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1 or whether it relies on separate subsystems for musical and verbal information remains debated,  
2 both in adults (Caclin & Tillmann, 2018; Gorin et al., 2016, 2018; Hirel et al., 2017) and  
3 children (Ginzburg et al., 2022). Taken together, for the aim to search for a common underlying  
4 impairment between dyslexia and amusia, these observations lead to propose STM as a  
5 potential candidate.

6         Second, the comorbidity between dyslexia and amusia could be due to a shared disorder  
7 of conscious access to existing domain-specific knowledge, namely, difficulties in becoming  
8 aware of and explicitly manipulating the constitutive units of speech or music, an hypothesis  
9 that has been put forward by Peretz (2016). We here use the term *auditory perceptual*  
10 *awareness* to designate this specific ability. In the language domain, this ability is typically  
11 assessed by *phonological awareness* tasks, such as syllable or phoneme counting, deletion,  
12 addition or reversal, as well as by the auditory acronym task, in which participants have to  
13 isolate the first phonemes of two spoken words and blend them to form a new word. All these  
14 tasks require grasping that speech can be analysed into sublexical units, namely syllables and  
15 phonemes. Reading in an alphabetic script is specifically contingent on the grasping of the  
16 *alphabetic principle*, namely of the intuition that graphemes (letters, alone or in combination  
17 such as <ch> in <chat>) stand for phonemes. This is not an easy venture, as, contrary to  
18 syllables, phonemes do not correspond to stable physical segments of speech (Liberman et al.,  
19 1967). Therefore, *phoneme awareness* (i.e., explicit representations of phonemes) develops  
20 hand in hand with the acquisition of the alphabetic principle, namely, with (alphabetic) reading  
21 acquisition (e.g., Morais et al., 1987a, b; Wimmer et al., 1991). Consistently, impaired phoneme  
22 awareness is one of the major features of the phonological deficit in dyslexia (e.g., Lundberg  
23 & Høien, 1989; Snowling, 1998; Swan & Goswami, 1997).

24         Similar awareness skills applied to the constituent units of music (interval and notes)  
25 are likely to underlie music processing. In line with this hypothesis, trained musicians

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1 demonstrate superior analytical listening skills compared to non-musicians, especially in  
2 explicitly analyzing the musical intervals that constitute a melody (Bever & Chiarello, 1974;  
3 Oxenham et al., 2003). To date, very few studies have attempted to compare within the same  
4 children the ability to operate explicitly on speech and music sound units. Two reports (Morais  
5 et al., 2010; Morais et al., 1984) have suggested that dyslexic children are poorer than typical  
6 readers in segmenting speech, but not in segmenting tone sequences. However, unlike the  
7 verbal segmentation task, the musical segmentation task used by Morais et al. (1984) had a  
8 strong visuo-motor component that could have masked potential auditory processing  
9 difficulties, and the small sample size of Morais et al. (2010; 8 dyslexic participants and 12 age-  
10 matched controls) limited potential conclusions. To our knowledge, the performance of amusic  
11 individuals has never been assessed with behavioural tasks specifically targeting auditory  
12 perceptual awareness. Yet, it has been reported that amusic individuals are deficient in  
13 evaluating the direction of a musical interval (Loui et al., 2008), a task that could be considered  
14 akin to an auditory perceptual awareness task, as one strategy is to divide the interval into two  
15 subunits (i.e., two notes), and then compare their respective pitch heights. In some ways, many  
16 of the psychoacoustic tasks in which amusic individuals have been shown to be impaired (e.g.,  
17 Foxton, 2004) require conscious access and some degree of manipulation of musical pitches.  
18 Their lack of conscious access to fine-grained pitch deviances marked by both an inability to  
19 detect them explicitly and abnormal attentive but normal pre-attentive neurophysiological  
20 responses (Moreau et al., 2013; Peretz et al., 2009; Zendel et al., 2015) further suggests that  
21 they may show an impairment in tasks requiring the conscious processing of music sound units.  
22 In a related vein, cases of comorbid dyslexia/amusia described in childhood showed particularly  
23 pronounced impairments in phonological awareness (as assessed by initial syllable or phoneme  
24 deletion tasks, syllable or phoneme inversion tasks, and auditory acronyms) compared to their  
25 peers with pure dyslexia, despite comparable severity of literacy impairments in these two

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1 subgroups (Couvignou & Kolinsky, 2021). This is consistent with two independent adult  
2 studies reporting severe phonological awareness difficulties (as assessed by syllable or  
3 phoneme deletion tasks, and auditory acronyms) in a subset of amusic individuals (Couvignou  
4 et al., 2019; Sun et al., 2017). More generally, phonological awareness correlates positively  
5 with pitch perception and production skills in school-aged children (Loui et al., 2011). Auditory  
6 perceptual awareness skills thus deserve further investigation in the study of the relationship  
7 between dyslexia and amusia.

8 Third, the comorbidity may be underpinned by a difficulty in paying attention to  
9 phonological information and pitch information. In this respect, auditory *sustained attention*  
10 and *selective attention*, two fundamental requirements for information processing, as well as  
11 *impulsivity*, are worth exploring. Sustained attention refers to a long-lasting mobilization of  
12 attentional resources. Selective attention, on the other hand, refers to the ability to focus on a  
13 limited array of all available sensory information. Both are closely related to working memory  
14 (Downing, 2000; Gazzaley & Nobre, 2012) and consciousness (De Brigard & Prinz, 2010;  
15 Koch & Tsuchiya, 2007; van Boxtel et al., 2010), and therefore are good candidates in the  
16 search for underlying impairment(s) common to dyslexia and amusia.

17 Impulsivity refers to a tendency to act in response to immediate stimuli, without  
18 deliberation or consideration of risks and consequences. Previous research has documented the  
19 frequent occurrence of impulsive behaviors in specific learning disorders (Al-Dababneh & Al-  
20 Zboon, 2018), but their exact role in the aetiology of these disorders is still debated. A variety  
21 of attention impairments has been reported in dyslexia, mainly in the visual domain, but also in  
22 the auditory domain (Facoetti et al., 2010; Lallier et al., 2009, 2010), as well as higher cognitive  
23 impulsivity in dyslexic children (Donfrancesco et al., 2005). To the best of our knowledge,  
24 however, no study has yet investigated attentional abilities comparatively for verbal and  
25 musical materials in the same group of dyslexic participants. In addition, as mentioned above,

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1 dyslexia and attention deficit / hyperactivity disorder co-occur frequently, with a comorbidity  
2 rate of around 30 % (Germanò et al., 2010). In amusia, sustained attention skills have been  
3 studied through electroencephalography, but only in relation to pitch awareness skills (Peretz  
4 et al., 2009; Zendel et al., 2015). Interestingly, abnormal neural responses to pitch deviance in  
5 a melody emerged in the amusic brain only when an explicit detection of the pitch deviances  
6 was required, but not when the task required a judgment on a different dimension (i.e., the  
7 detection of unrelated clicks; Zendel et al 2015, see also Tillmann, Lalitte et al., 2016, for  
8 converging evidence with behavioral methods). This observation suggests that auditory  
9 attention skills of amusic individuals are functional, but interfere with explicit pitch perception  
10 judgements. In a related vein, Moreau and collaborators (2013) observed that large pitch  
11 changes (but not small ones) were correctly detected and generated normal P300 in amusics,  
12 supporting the view that their pitch perception impairment cannot be explained solely by a lack  
13 of attentional resources or a general unresponsiveness to pitch variations. Nevertheless, the role  
14 of attentional skills remains an important issue and is worthy of further investigation.

15         These three cognitive functions (i.e., auditory short-term memory, perceptual  
16 awareness, and attention) have already been investigated in studies on either dyslexia or amusia,  
17 but as far as we know, not together. Previous studies examined either the language or the music  
18 domain, hence each disorder separately. In addition, they used various dimensions, paradigms,  
19 stimuli, and tasks that are not easily comparable across these domains.

20         In the present study, we developed a battery of behavioral tests aiming to characterize  
21 the overlap of potential impairments of auditory memory, perceptual awareness, and attention  
22 applied to both linguistic and musical materials. These functions were examined in parallel, for  
23 each of the domains of specificity of both disorders (syllables and phonemes; musical intervals  
24 and notes). As in Tillmann et al. (2009), the generality of the impairments was further assessed  
25 with a third auditory control material, namely timbre. Importantly, all the tasks were based on

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1 the same set of stimuli, so that any performance difference between tasks would most likely  
2 reflect differences at higher processing levels rather than in early/perceptual processing. The  
3 battery was administered to four groups of participants: dyslexic children with amusia  
4 (henceforth, DYS+A), dyslexic children without amusia (henceforth, DYS-A, of equivalent age  
5 and reading level as DYS+A children), and two control groups of typical readers without  
6 amusia matched to the two groups of dyslexic participants for either chronological age or  
7 reading level (henceforth, CA controls and RL controls, respectively).

8 Comparing these four groups of participants, and in particular DYS+A and DYS-A  
9 children to the two control groups, should allow us to identify possible connections and thus  
10 pointing to potentially causal underlying impairments. As discussed by Goswami (Goswami,  
11 2003, 2015; Goswami & Bryant, 1989) and Huettig et al. (2018), numerous impairments that  
12 have been proposed as underlying dyslexia (e.g., poor phonological awareness and low verbal  
13 STM, but also sensory impairments such as magnocellular deficit, or impairments in visual  
14 attention) might actually result from (rather than cause) the effects of reduced reading  
15 experience. This illustrates why the RL control group is critical: “if children with dyslexia  
16 perform worse than the younger reading level-matched children, this suggests a causal role for  
17 the factor being investigated, as the children with dyslexia have higher chronological and  
18 mental ages and better metacognitive skills” (Goswami, 2015 p. 44). Subsequent longitudinal  
19 and training studies are then required to properly test the causal hypothesis. In the present study,  
20 we thus considered that only a difference between dyslexic children and *both* control groups  
21 would suggest a causal role for the cognitive function at stake.

22 However, not all dyslexic children would necessarily present such impairment(s) in both  
23 the language and music domains. Namely, if developmental dyslexia and congenital amusia  
24 were sharing common underlying impairment(s) with regards to some specific cognitive  
25 function(s), we would expect at least the DYS+A children to differ from both the CA and RL

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1 controls on that or those function(s), whatever the domain investigated. DYS-A children might  
2 also show an impairment in that or those function(s), but to a lesser degree or only in the  
3 language domain. In short, we thus attempted to identify an impairment in one or several of the  
4 three investigated cognitive functions that would manifest itself in both language and music at  
5 least in DYS+A children and potentially, although to a lesser extent, in the DYS-A children.

6 If dyslexia and amusia shared common underlying impairment(s), the following  
7 predictions should be confirmed. First, dyslexic children should present a marked impairment  
8 for one or several specific function(s), manifesting itself in each of the domains of specificity  
9 of both disorders (phonemes and pitches) and possibly in timbres, whose processing has  
10 sometimes been reported to be deficient in amusia (Marin et al., 2012; Tillmann et al., 2009).  
11 In the verbal domain, the common underlying impairment(s) are expected to be observed in  
12 both the DYS+A and DYS-A children. In the musical domain, they are expected to be  
13 particularly pronounced in the DYS+A children but may be observed in the DYS-A children as  
14 well, although to a lesser extent. In addition, if common cognitive impairment(s) are core  
15 impairments inherent to dyslexia, they should be observed independently of reading experience  
16 and thus be revealed relative to both the CA and the RL control groups (Goswami, 2015;  
17 Huettig et al., 2018). At an individual level, we expect such impairments to affect most cases,  
18 rather than group differences being driven by a small number of poor performers. Finally, we  
19 expect to observe correlational links between participants' performance in the function(s) at  
20 play and their reading/musical skills.

## 21 **Methods**

### 22 **Participants**

23 Eighty-six children were recruited for this study, but six (3 dyslexic and 3 control  
24 candidates) were excluded based on the inclusion phase tests described below. Fifteen DYS+A  
25 children and 15 DYS-A children aged between 7 and 13 years were included, as well as 25 CA

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1 controls and 25 RL controls<sup>1</sup>. All were French native speakers born in Belgium or in France  
2 who reported normal hearing and normal or corrected-to-normal vision, and all had nonverbal  
3 IQ above percentile 10 (as estimated with the Raven's Colored Progressive Matrices (Raven,  
4 1965), see *inclusion phase* below). They attended school regularly and none of them reported  
5 any history of neurological illness or brain damage. The dyslexic children were recruited from  
6 either specialist or public elementary schools in Belgium and in France. They previously had  
7 received a formal diagnosis of dyslexia by a speech therapist and were receiving or had received  
8 speech therapy. The controls were selected from public elementary schools in the same cities  
9 as the dyslexic children or through personal networks; none of them had a history of written  
10 language impairment. Some of the participants (10 DYS+A, 7 DYS-A, and 9 CA controls) had  
11 previously participated in a related study (Couvignou & Kolinsky, 2021). The four groups were  
12 matched for sex ratio, music education (as measured by years of extracurricular music  
13 instruction), parents' socio-economic status, and nonverbal IQ (Table 1).

14 Inclusion criteria required children with dyslexia to score at least 1.5 standard deviation  
15 (SD) below the grade-appropriate mean in either text or isolated word reading (accuracy or  
16 speed; Jacquier-Roux et al., 2005) and CA control participants to score no more than 1 SD  
17 below the mean in both tests. In addition to reading abilities, phonological processing was  
18 assessed in dyslexic and CA control participants at the inclusion phase. All participants  
19 completed the abbreviated version of the *Montreal Battery of Evaluation of Musical Abilities*

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<sup>1</sup> For our study to have 80% power to detect an effect with a Cohen's  $f$  of 0.1 and a significance level of .05, 22 participants were required in each group (calculation performed for a mixed ANOVA under G\*Power 3; Faul et al., 2007). The final sample satisfied these requirements for CA and RL groups, but not for DYS+A and DYS-A groups, due to the great difficulty in recruiting these children. Note that our sample size still exceeds that of comparable studies conducted with these particular populations (e.g., Graves et al., 2019; Lagrois & Peretz, 2019; Lazzaro et al., 2021; Tao et al., 2019).

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1 (MBEMA, Peretz et al., 2013), a battery designed to assess melody, rhythm, and music  
2 incidental memory skills in school-aged children (see inclusion phase below for a detailed  
3 description). Participants were considered amusic when they scored 2 SD below the mean of  
4 controls of the same age (i.e., based on CA controls' scores for dyslexic and CA control  
5 participants, and based on RL controls' scores for RL control participants) in the melodic task  
6 or across the three tasks of the MBEMA<sup>2</sup>. Note that two DYS+A children also had a formal  
7 diagnosis of attention deficit disorder (ADD). Therefore, where appropriate, the influence of  
8 these children's performance was controlled for in the relevant analyses (see results section).  
9 No other comorbidities were reported among the participants.

10         The study was conducted with approval of the local Ethics committee of the Université  
11 Libre de Bruxelles (agreement number: 034/2017) and was performed in accordance with the  
12 principles stated in the Declaration of Helsinki. Written informed consent was obtained from  
13 the parents of each child, as well as oral agreement from each participant prior to the study  
14 participation. All children received a “diploma” as a reward for their time and participation. In  
15 the context of the COVID-19 pandemic, necessary precautions have been taken to avoid  
16 contaminations including appropriate protection sanitary measures (remote body temperature  
17 measurement, hand and material disinfection, safety interpersonal distance, mask wearing, and  
18 regular ventilation). Also, parents signed an additional consent form in which they explicitly

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<sup>2</sup> Using the cutoffs of Peretz et al. (2013), the categorization remained the same for all participants except three DYS+A children (S038, S040, and S054), who performed above the threshold of -2 SD for both global and melodic scores by these norms and would therefore be considered non-amusic. Following previous studies defining the diagnostic criterion for amusia based on a matched control group (see Vuvan et al., 2018, for a review of methods for identifying amusia using the MBEA), we kept them in the DYS+A group. Indeed, this method has the advantage of controlling for the effects of several cognitive and demographic variables that may influence musical performance such as IQ, SES, or level of musical education.



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1 consented to their name being communicated to the accredited federal service if needed in case  
2 of a known positive contact or infection.

3 *- Insert Table 1 here -*

### 4 **Materials and Procedure**

5 Children were tested individually in a quiet room of their school or home, over three sessions  
6 of about one hour each (or six sessions of 30 minutes each, for the youngest ones), with a few  
7 days between sessions. The inclusion tests were administered in the first session, and the  
8 experimental tests were distributed over the other sessions. The 26 children who participated in  
9 a previous study (Couvignou & Kolinsky, 2021) were not presented with the inclusion tests  
10 again if their data had been acquired less than one year before the present testing phase, with  
11 the exception of the *Mécanisme d'Identification des Mots* (MIM, “Word Identification  
12 Mechanism”) reading subtest (see inclusion phase below for more details), which was not part  
13 of the previous battery. All tasks were programmed under *PsychoPy2* (Peirce et al., 2019),  
14 except for nonverbal intelligence, reading, and rapid naming tests, which were administered in  
15 paper form. Stimuli were presented through *Sennheiser HD206* headphones at a comfortable  
16 subjective loudness level.

17 The evaluations were conducted by the first author or by one of the four Master students  
18 involved in the project. To minimize inter-experimenter variability and to agree on how to  
19 interact with the children, precise written instructions were provided in advance and the first  
20 week of evaluation was conducted under the direct supervision of the first author. All  
21 experimenters tested participants of all groups, to eliminate the potential source confounding  
22 between group and experimenter differences.

### 23 ***Inclusion Phase***

24 The *inclusion phase* consisted of a set of tasks aimed at assessing nonverbal intelligence,  
25 reading accuracy and speed, phonology, and musical skills.

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1           Nonverbal intelligence was assessed using the Raven’s Colored Progressive Matrices  
2 (Raven, 1965). In this test, children were presented with an incomplete picture and six  
3 alternatives among which they must choose the one that best completes the picture. The test  
4 consisted of 36 visual patterns of increasing difficulty. French norms (Raven, 1998) were used  
5 to convert raw scores to age-standardized scores and to ensure that all children performed above  
6 percentile 10.

7           Reading accuracy and speed were assessed in all participants using the MIM subtest of  
8 the *Batterie d’Évaluation du Langage Écrit* (BELEC, Written Language Assessment Battery;  
9 Mousty et al., 1994), which evaluates reading of lists of 72 isolated words and pseudowords  
10 varying in length, frequency, and complexity. In addition, dyslexic and CA control participants  
11 took two complementary standardized reading tests from the French Battery *Outil de Dépistage*  
12 *des Dyslexies* (ODEDYS, Dyslexia Screening Tool; Jacquier-Roux et al., 2005). In the *text*  
13 *reading* test, children were asked to read aloud the text “Monsieur Petit” for one minute. The  
14 number of words read without error was scored. In the *word/pseudoword reading* test, children  
15 were administered three lists of 20 items each: irregular words, regular words and pseudowords.  
16 They were asked to read them aloud as quickly and as accurately as possible. Both accuracy  
17 and speed were scored.

18           Phonological skills were investigated with tests of phonological memory, phonological  
19 awareness, and rapid access to phonological information in dyslexic and CA control  
20 participants. Phonological memory was estimated with the *pseudoword repetition* tests of the  
21 BELEC (Mousty et al., 1994), even though this task cannot be considered a pure measure of  
22 phonological memory, as it also involves phonological discrimination, phonological  
23 programming, and articulation skills. Children were instructed to repeat recorded pseudowords  
24 of increasing length (1 to 5 syllables) as accurately as possible. Five series of four items each  
25 were presented under two conditions: the pseudowords’ syllables had either a simple structure

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1 (consonant-vowel, CV condition) or a complex one (consonant-consonant-vowel, CCV  
2 condition). The number of pseudowords repeated without error was scored. In the *initial*  
3 *syllable deletion* and *initial phoneme deletion* tests of the BELEC (Mousty et al., 1994),  
4 children were required to repeat CVCV pseudowords without the initial syllable (16 items) as  
5 well as to repeat CVC (16 items) and CCV (10 items) monosyllables without the initial  
6 phoneme. Four practice trials were given before each condition. The score was the total number  
7 of correct answers. Rapid access to phonological and lexical information was evaluated through  
8 a Rapid Automatized Naming (RAN) task, in which children named as fast as possible two  
9 series of 50 objects each. The score was the sum of total naming time for both series.

10 Musical skills were assessed using the abbreviated version of the *Montreal Battery of*  
11 *Evaluation of Musical Abilities* (MBEMA, Peretz et al., 2013), which involves two tests  
12 evaluating melody and rhythm processing, as well as one test examining incidental memory of  
13 unfamiliar tonal melodies. Each test comprised two practice trials with feedback followed by  
14 20 experimental trials and used the same pool of 20 unfamiliar melodies that were written  
15 according to the rules of the Western tonal system. The *Melody* and *Rhythm* tests involved pairs  
16 of melodies and consisted of a same-different judgement. The *Memory* test required children to  
17 recognize a melody as having been presented earlier during the session or not. The score was  
18 the total number of correct answers. Note that the 26 children from our previous study had taken  
19 the full version of this battery, which involves three tests of melody processing instead of one  
20 (see Peretz et al., 2013 for a detailed description). For the *Melody* test, their results were  
21 converted so that only the trials present in the abbreviated version were included in the score  
22 calculation. For the *Rhythm* and *Memory* tests, the original score was kept.

23 Average performance on the tests used in the inclusion phase are presented in Table 1.

### 24 *Experimental Phase*

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1           The experimental phase was presented in the form of three computer games: “Spot the  
2 difference”, “The missing wagon”, and “The sound hunter”, which respectively aimed to assess  
3 auditory STM, perceptual awareness, and attention skills in a comparative way for the three  
4 materials: words, tones, and timbres. The tasks were based on the same set of stimuli, a detailed  
5 description of which can be found in Schulze and Tillmann (2013). For the word tasks, six  
6 monosyllabic meaningful French words were used (CV combination, using the vowel /u/; that  
7 is: /bu/, /gu/, /lu/, /mu/, /pu/, and /tu/), all spoken by a female voice and adjusted to the pitch of  
8 230 Hz. For the pitch tasks, six tones differing in pitch height were used, namely C4 (262 Hz),  
9 D4 (294 Hz), E4 (330 Hz), F4 (349 Hz), G4 (392 Hz), and A4 (440 Hz), all generated with a  
10 piano timbre. For the timbre tasks, we used six timbres (cello, flute, guitar, piano, trumpet, and  
11 vibes), all played at 330 Hz (E4). The stimuli of each material had a duration of 500 ms each  
12 and were subjectively equalized in loudness. Children were sensitized to the stimuli before  
13 starting the tests, with a short *minimal pair discrimination* task involving the least salient  
14 contrasts (i.e., linguistic pairs differing only by a single phonetic feature: /bu/ - /gu/, /pu/ - /bu/,  
15 /tu/ - /pu/; pitch pairs separated by one tone or semitone: C4 - D4, E4 - F4, G4 - A4; and the  
16 (subjectively) more similar timbres: cello - flute, guitar - piano, vibes - guitar). The task  
17 included 18 trials presented in a fixed order: 6 pairs for each material (word, pitch, timbre),  
18 with half of them being “same” trials and the other half being “different” trials. Feedback was  
19 given after each trial, together with the option to listen to the trial again in case of failure. A 6-  
20 point discrimination score was calculated for each material.

21           **Auditory STM** was assessed using a recognition paradigm based on Schulze and  
22 Tillmann (2013; Figures 1A, 2A), but the task was adapted to children in terms of length by  
23 reducing the numbers of trials and the number of items per sequence. In addition, we  
24 investigated item memory separately from order memory, because phonological representations  
25 are thought to be involved differently in these two types of tasks (Majerus & Cowan, 2016).

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1 The child listened to pairs of auditory sequences separated by a 2-second silent interval and had  
2 to judge by pressing one of the two response keys (on the left or right side of the keyboard)  
3 whether the pairs were the same or different. The next trial automatically started 2 seconds after  
4 the child had given his/her answer. Throughout the test, the child was asked to keep his/her  
5 index fingers on the response keys in order to avoid any delay due to reaching the key. Two  
6 experimental conditions were contrasted without the child's knowledge. In the *item condition*,  
7 the incorrect trials were constructed by exchanging a single item of the second sequence (e.g.,  
8 A B C - A D C). In the *order condition*, the incorrect trials were constructed by switching the  
9 position of two adjacent items in the sequence (e.g., A B C - A C B). Each of these two  
10 conditions were tested separately in three randomized blocks (one for each material), each of  
11 the blocks themselves being divided into three levels of memory load, depending on the length  
12 of the to-be-remembered sequence (3, 4, and 5 items of 500 ms each per sequence respectively,  
13 with an inter-stimulus interval of 20 ms). In line with previous studies reporting sequence length  
14 effects for both verbal and musical materials (Gorin et al., 2018; Schulze & Tillmann, 2013),  
15 we expected performance to decrease with increased memory load (i.e., increased sequence  
16 length). Two sets of trials were used, which were counterbalanced over participants and  
17 conditions (i.e., half of the participants were tested with set 1 in the item condition and set 2 in  
18 the order condition, the other half of participants with set 2 in the item condition and set 1 in  
19 the order condition). Both sets respected the following constraints: (i) an item was never used  
20 twice within the same sequence, (ii) the occurrence of item by position was balanced, so that  
21 each item was presented once in each position of the sequence, and (iii) the first item of the  
22 second sequence was never changed for different trials to prevent participants from solving the  
23 task by comparing only the first item of the two sequences. Pitch material implied additional  
24 constraints in terms of melodic contour: (iv) the melodic contour of the initial sequences was  
25 balanced between the two sets and the two conditions (i.e., the same alternating descending and

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1 ascending patterns were used for the construction of the initial sequences of both sets and both  
2 conditions), and (v) “different” trials systematically induced at least one contour change in the  
3 sequence. Post-hoc analyses conducted on the mean size of the interval change and the mean  
4 number of contour changes showed that overall, for the pitch material, the changes were not  
5 comparable across conditions and lengths (see detailed results in Supplementary Material S1).

6         The pattern of sequence pairs of the pitch material served as a template to generate the  
7 sequence pairs for the word and timbre materials. The task was presented to participants with  
8 two three-item sequence trials (one same, one different) at the beginning of each block.  
9 Feedback was given for these practice trials only, together with the option to listen to the trials  
10 again. In total, the task included 216 experimental trials: 12 pairs for each condition (item,  
11 order), material (word, pitch, timbre), and length (3, 4, 5), with half of them being same trials  
12 and the other half being different trials. A pseudo-randomized presentation was used so that: (i)  
13 a given sequence could not be presented on consecutive trials and (ii) the type of pair (same,  
14 different) changed after at most three trials (i.e., no more than three consecutive “same” or  
15 “different” trials). To avoid fatigue, the two conditions (item, order) were not tested within the  
16 same experimental session but spread over two different sessions a few days apart. Each session  
17 lasted about 30 minutes.

18         **Auditory Perceptual Awareness** was assessed using a recognition paradigm inspired  
19 by Morais et al. (2010; Figures 1B, 2B, 2C). Based on that study, we decided to use a  
20 correctness judgment task to minimize memory load. The child listened to pairs of auditory  
21 sequences separated by a 2-second silent interval and had to judge by pressing one of the two  
22 response keys (on the left or right side of the keyboard) whether or not the second sequence  
23 was correctly repeated without the first element. The next trial automatically started 2 seconds  
24 after the child had given his/her answer. Throughout the test, the child was asked to keep his/her  
25 index fingers on the response keys in order to avoid any delay due to reaching the key. For the

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1 word and the pitch tasks, the sequences were composed of two large perceptual units (e.g., 2  
2 syllables or 2 musical intervals), each of which could be divided into two smaller subunits (e.g.,  
3 2 phonemes or 2 notes). The task had to be performed at the level of either large or small  
4 perceptual units, which was illustrated to the child using drawings of train wagons of varying  
5 lengths (Figures 2B, 2C). We also used a control condition involving timbre processing, in  
6 which the sequences were composed of two timbres. Each syllable, note, and timbre lasted 500  
7 ms: consequently, the duration of the sequences was unequal across materials (i.e., each  
8 sequence lasted 1000 ms for word and timbre materials but 2000 ms for pitch material). This  
9 choice was made to privilege the matching of the materials in terms of number of perceptual  
10 units. As in the STM task, two experimental conditions (item and order) were contrasted  
11 without the child's knowledge, depending on how the incorrect trials were built, namely on the  
12 basis of a manipulation of either item identity or presentation order (see Figure 1B for an  
13 example for each material and condition). These two conditions were tested separately in five  
14 blocks (syllable, phoneme, interval, note, timbre) using a pseudo-randomized order so that the  
15 syllable material always preceded the phoneme one and the interval material always preceded  
16 the note one. In this way, the condition involving the largest perceptual units (assumed to be  
17 easier to achieve) was always presented first. Again, two sets of trials were used, which were  
18 counterbalanced over participants and conditions. Both sets respected the following constraints:  
19 (i) an item was never used twice within the same sequence, (ii) the occurrence of item by  
20 position was balanced, so that each item was presented once in each position of the sequence.  
21 For a closer match between word and pitch materials, (iii) the same initial sequences were used  
22 for syllable and phoneme, as well as for interval and note, and (iv) incorrect propositions were  
23 always created by a change located on the third subunit of the initial sequence (i.e., third  
24 phoneme or third note). In addition, for pitch material, (v) the melodic contour of the initial  
25 sequences was balanced between the two sets and the two conditions (i.e., the same alternating

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1 descending and ascending patterns were used for the construction of the initial sequences of  
2 both sets and both conditions). Given all these constraints and the limited number of items, the  
3 “different” trials did not always induce a contour change in the sequence. Control analyses  
4 showed that the mean size of the interval change was significantly lower for the interval than  
5 for the note material (see detailed results in Supplementary Material S2). Hence, any difference  
6 in performance between these two materials should be interpreted with caution, as better  
7 performance might be linked to bigger changes in note material. The task was demonstrated  
8 with four trials (two correct, two incorrect) at the beginning of each block. Feedback was given  
9 for these practice trials only, together with the option to listen to the trial again. In total, the task  
10 included 120 experimental trials: 12 pairs for each condition (item, order), and material  
11 (syllable, phoneme, interval, note, timbre), with half of them being correct and the other half  
12 being incorrect. A pseudo-randomized presentation was used so that: (i) a given sequence could  
13 not be presented on consecutive trials and (ii) the type of pair (correct, incorrect) changed after  
14 at most three trials (i.e., no more than three consecutive “correct” or “incorrect” trials). Again,  
15 to avoid fatigue, the two conditions (item, order) were not tested within the same experimental  
16 session but spread over two different sessions a few days apart. Each one lasted about 20  
17 minutes.

18 **Auditory Attention** was assessed using a go/no-go paradigm (Figures 1C, 2D). The  
19 child listened to a series of sounds presented at regular time intervals (items of 500 ms each,  
20 with an inter-stimulus interval of 1 s) and had to press a response key as soon as he/she heard  
21 a target sound. Throughout the test, the children were asked to keep their index finger on the  
22 response key so that they could press it as soon as they heard the target. The task consisted of  
23 three randomized blocks (one for each material), each divided into two levels of difficulty. At  
24 level 1, the target had to be distinguished from a single distractor (i.e., /lu/ among /pu/; A4  
25 among E4; flute among vibes). At level 2, the same target had to be identified among three



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1 different distractors (i.e., /lu/ among /pu/, /gu/, and /tu/; A4 among E4, D4, and C4; flute among  
2 vibes, cello, and guitar), making the identification of the stimuli more demanding on the  
3 memory level and involving selective attentional skills to a greater extent. To minimize the role  
4 of discrimination abilities in task performance, distractors were chosen to be as distinct as  
5 possible from the target, in terms of phonetic features, pitch height or family of musical  
6 instruments (woodwind, percussion, bowed strings, or plucked strings). Before each level of  
7 each block, the target was presented to the child in isolation, followed by 15 practice trials (3  
8 targets to be found among 12 distractors at level 1, or among 3 different distractors presented 4  
9 times each at level 2) for which feedback was given. In total, the task included 720 experimental  
10 trials: 120 for each material (word, pitch, timbre) and level (1, 2) including 24 targets and 96  
11 distractors (or 3 distractors presented 32 times each at level 2), so that the target/distractor ratio  
12 was kept constant. Note that the target/distractor ratio (1/4) was intentionally kept low, in order  
13 to more specifically assess vigilance and sustained attention rather than inhibition. The  
14 experimental trials were carried out without feedback. The whole task lasted about 30 minutes.

15 *- Insert Figure 1 here -*

16 *- Insert Figure 2 here -*

### 17 **Data Analysis**

18 Auditory STM and perceptual awareness, as well as attention performance were  
19 assessed using Signal Detection Theory (Macmillan & Creelman, 2004). We calculated  $d'$   
20 sensitivity index as  $d' = z(H) - z(FA)$  for each participant as a function of each condition,  
21 material, sequence length, and/or level. Hits and false alarms (FAs) were defined as follows:  
22 for the auditory STM tasks,  $H = p(\text{response} = \text{different} \mid \text{stimulus} = \text{different})$  and  $FA = p$   
23  $(\text{response} = \text{different} \mid \text{stimulus} = \text{same})$ ; for the auditory perceptual awareness tasks,  $H = p$   
24  $(\text{response} = \text{incorrect} \mid \text{stimulus} = \text{incorrect})$  and  $FA = p(\text{response} = \text{incorrect} \mid \text{stimulus} =$   
25  $\text{correct})$ ; and for the auditory attention tasks,  $H = p(\text{response} = \text{target} \mid \text{stimulus} = \text{target})$  and

1  $FA = p$  (response = target | stimulus = distractor). To avoid infinite  $d'$  values, proportions of 0  
2 and 1 were adjusted to  $1/(2N)$  and  $1 - 1/(2N)$ , respectively, where  $N$  is the number of trials on  
3 which the proportion is calculated. One RL control was excluded from the STM analyses and  
4 one RL control from the auditory perceptual awareness analyses because they probably did not  
5 understand the task<sup>3</sup>.

## 6 **Results**

### 7 **Group Comparisons**

#### 8 *Minimal Pair Discrimination*

9 This task refers to the short discrimination test designed to make children aware of the  
10 different contrasts between the stimuli before starting the other tests. DYS+A children  
11 performed significantly worse than both DYS-A children and CA controls but not significantly  
12 different from RL controls for pitch material (Table 2). No other group difference was  
13 significant.

14 *- Insert Table 2 here -*

#### 15 *Auditory STM*

16 To explore the potential role of auditory STM in the comorbidity between dyslexia and  
17 amusia, a 2 (Condition: item, order) x 3 (Material: word, pitch, timbre) x 3 (Sequence length,  
18 henceforth Length: 3, 4, or 5 items per sequence) x 4 (Group: DYS+A children, DYS-A

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<sup>3</sup> Both presented a mean  $d'$  of zero in the easiest conditions (i.e., for the STM tests: in the item condition for length 3 across materials, and for the auditory perceptual awareness tests: in the item condition across materials), while all other participants were quite able to perform the task with mean  $d'$  scores in the easiest STM tests of 2.2 (SD = 0.8), 2.6 (SD = 0.5), 2.8 (SD = 0.6), and 2.0 (SD = 0.8) for DYS+A children, DYS-A children, CA controls, and RL controls respectively, and mean  $d'$  scores in the easiest auditory perceptual awareness tests of 1.3 (SD = 0.6), 2.2 (SD = 0.5), 2.4 (SD = 0.5), 2.4 (SD = 0.6), and 1.8 (SD = 0.7) for DYS+A children, DYS-A children, CA controls, and RL controls, respectively.

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1 children, CA controls, RL controls) mixed-design analysis of variance (ANOVA) was  
2 computed on the  $d'$  sensitivity index, with condition, material, and length as within-participant  
3 factors and group as between-participants factor. Table 3 summarizes the outcomes of this  
4 analysis and Figure 3 presents the average  $d'$  values.

5 *- Insert Figure 3 here -*

6 The ANOVA revealed significant main effects of condition,  $F(1, 75) = 23.05, p < .001,$   
7  $\eta^2_p = .235,$  material,  $F(2, 150) = 57.00, p < .001, \eta^2_p = .432,$  length,  $F(2, 150) = 222.16, p <$   
8  $.001, \eta^2_p = .748,$  and group,  $F(3, 75) = 8.39, p < .001, \eta^2_p = .251,$  as well as significant  
9 interactions between condition and length,  $F(2, 150) = 7.45, p < .001, \eta^2_p = .090,$  material and  
10 length,  $F(4, 300) = 3.34, p = .011, \eta^2_p = .043,$  length and group,  $F(6, 150) = 2.52, p = .024, \eta^2_p$   
11  $= .091,$  and material and group,  $F(6, 150) = 2.54, p = .023, \eta^2_p = .092.$  In addition, significant  
12 3-way interactions were observed between condition, material, and length,  $F(4, 300) = 3.34, p$   
13  $= .011, \eta^2_p = .043,$  and between condition, length, and group,  $F(6, 150) = 4.15, p < .001, \eta^2_p =$   
14  $.142.$  No other interaction was significant (all  $F_s < 1$  except for Condition x Group:  $F(3,75) =$   
15  $1.88, p = .141,$  and Condition x Material x Length x Group:  $F(12, 300) = 1.56, p = .103).$   
16 Additional analyses, presented in Supplementary Material S3.1, showed that the lower pitch  
17 discrimination performance of DYS+A children (Table 2) did not influence this pattern of  
18 results.

19 The absence of the Condition x Material x Length x Group interaction was further  
20 investigated by performing Bayesian analyses. Indeed, a key advantage of the Bayes factor over  
21 the  $p$ -value is that, unlike the  $p$ -value, the Bayes factor can lead to support for the null  
22 hypothesis as well as the alternative hypothesis. A 2 (Condition) x 3 (Material) x 3 (Length) x  
23 4 (Group) Bayesian mixed-design ANOVA was conducted on  $d'$ , with condition, material, and  
24 length as within-participant factors and group as between-participants factor. An analysis of  
25 specific effects showed a medium  $BF_{\text{exclusion}}$  score for the interaction between condition,

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1 material, length, and group ( $BF_{\text{exclusion}} = 8.53$ ), providing positive (Raftery, 1995) or even  
2 substantial (Jeffreys, 1961) evidence in favor of the absence of such interaction.

3       Regarding the interaction between material and group, post-hoc comparisons indicated  
4 that DYS+A children showed impaired STM for both words and pitches compared to typical  
5 readers of the same age, without differing from typical readers of the same reading level. For  
6 pitches, this impairment was also observed in comparison with their DYS-A peers. However,  
7 it did not extend to timbres. In contrast, DYS-A children showed no impairment in auditory  
8 STM compared to the other groups. In addition, an age effect<sup>4</sup> was observed for pitches, with  
9 CA controls performing better than RL controls on this material, but not for words or timbre.  
10 These analyses are presented in detail in Supplementary Material S3.2.

11       Regarding the 3-way interaction between condition, material, and length, the  
12 performance difference between the item and order conditions was length dependent for words  
13 and timbres, but not for pitches (see detailed results in Supplementary Material S3.3). This  
14 interaction will not be detailed here because it does not involve group differences.

15       The 3-way interaction between condition, length, and group was further investigated by  
16 performing two separate 3 (Length) x 4 (Group) mixed-design ANOVAs on the item and order  
17 conditions, averaging across materials.

18       In the item condition, the ANOVA revealed main effects of length,  $F(2, 150) = 179.26$ ,  
19  $p < .001$ ,  $\eta^2_p = .705$ , and group,  $F(3, 75) = 7.38$ ,  $p < .001$ ,  $\eta^2_p = .228$ , but the interaction failed  
20 to reach significance,  $F(6, 150) = 2.09$ ,  $p = .058$ . Post-hoc comparisons indicated that DYS+A  
21 children showed a general item STM impairment compared to typical readers of the same age  
22 but not to typical readers of the same reading level. In contrast, DYS-A showed no item STM  
23 impairment across materials. In addition, an age effect was observed, with CA controls

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<sup>4</sup> Note that for sake of simplicity throughout the paper we report the difference between CA and RL controls as an age effect although it may actually be linked to school acquisitions, including literacy acquisition.

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1 performing better than RL controls. These analyses are presented in detail in Supplementary  
2 Material S3.4.

3 In the order condition, the ANOVA revealed main effects of length,  $F(2, 150) = 88.64$ ,  
4  $p < .001$ ,  $\eta^2_p = .542$ , group,  $F(3, 75) = 6.97$ ,  $p < .001$ ,  $\eta^2_p = .218$ , and a significant interaction  
5 between length and group,  $F(6, 150) = 4.23$ ,  $p < .001$ ,  $\eta^2_p = .145$ . Post-hoc comparisons revealed  
6 that DYS+A children showed a general auditory serial-order STM impairment for length 3  
7 compared to their DYS-A peers and typical readers of both the same age and the same reading  
8 level, and for length 4 compared to typical readers of both the same age and the same reading  
9 level. In contrast, DYS-A children showed no serial-order STM impairment across materials.  
10 No age effect was observed, CA controls performing not significantly different from RL  
11 controls for all sequence lengths. These analyses are presented in detail in Supplementary  
12 Material S3.5.

### 13 *Auditory Perceptual Awareness*

14 To explore the potential role of auditory perceptual awareness in the comorbidity  
15 between dyslexia and amusia, a 2 (Condition: item, order) x 5 (Material: syllable, phoneme,  
16 interval, note, timbre) x 4 (Group: DYS+A children, DYS-A children, CA controls, RL  
17 controls) mixed-design ANOVA was computed on the  $d'$  sensitivity index, with condition and  
18 material as within-participant factors and group as between-participants factor. The outcomes  
19 of this analysis are summarized in Table 3 and average  $d'$  values are shown in Figure 4.

20 - Insert Figure 4 here -

21 The ANOVA revealed significant main effects of condition,  $F(1,75) = 9.88$ ,  $p = .002$ ,  
22  $\eta^2_p = .116$ , material,  $F(4, 300) = 56.21$ ,  $p < .001$ ,  $\eta^2_p = .428$ , and group,  $F(3, 75) = 10.56$ ,  $p <$   
23  $.001$ ,  $\eta^2_p = .297$ , as well as a significant interaction between condition and material,  $F(4, 300)$   
24  $= 23.27$ ,  $p < .001$ ,  $\eta^2_p = .237$ , and a 3-way interaction between condition, material, and group,  
25  $F(12, 300) = 1.81$ ,  $p = .047$ ,  $\eta^2_p = .067$ . No other interaction was significant (all  $F$ s  $< 1$  except

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1 for Material x Group:  $F(12, 300) = 1.13, p = .338$ ). Similarly to the STM task, additional  
2 analyses showed that the lower pitch discrimination performance of DYS+A children did not  
3 influence this pattern of results (Supplementary Material S4.1). The 3-way interaction was  
4 further investigated by performing five separate 2 (Condition) x 4 (Group) mixed-design  
5 ANOVAs on each material.

6 For syllables, the ANOVA revealed main effects of condition,  $F(1,75) = 8.42, p = .005$ ,  
7  $\eta^2_p = .101$ , and group,  $F(3,75) = 7.59, p < .001, \eta^2_p = .233$ , but no significant interaction ( $F <$   
8  $1$ ). Post-hoc comparisons indicated impaired syllable awareness in DYS+A children compared  
9 to typical readers of the same age, but not to children with the same reading level. In contrast,  
10 DYS-A children showed no impairment in syllable awareness compared to the controls. In  
11 addition, it can be noted that syllable awareness performance was age sensitive, with CA  
12 controls performing better than RL controls. These analyses are presented in detail in  
13 Supplementary Material S4.2.

14 For phonemes, the ANOVA revealed main effects of condition,  $F(1,75) = 27.20, p <$   
15  $.001, \eta^2_p = .266$ , and group,  $F(3,75) = 3.51, p = .019, \eta^2_p = .123$ , but no significant interaction  
16 ( $F = 2.39, p = .076$ ). Post-hoc comparisons indicated impaired phoneme awareness in DYS+A  
17 children compared to typical readers of the same age, but not of the same reading level. In  
18 contrast, DYS-A children showed no impairment in phoneme awareness compared to the  
19 controls. In addition, phoneme awareness performance was not age sensitive, with CA controls  
20 performing not significantly different from RL controls. These analyses are presented in detail  
21 in Supplementary Material S4.3.

22 For intervals, the ANOVA revealed main effects of condition,  $F(1,75) = 36.56, p < .001$ ,  
23  $\eta^2_p = .328$ , and group,  $F(3,75) = 9.22, p < .001, \eta^2_p = .269$ , but no significant interaction ( $F =$   
24  $1.98, p = .124$ ). Post-hoc comparisons indicated impaired interval awareness in DYS+A  
25 children compared to both their DYS-A peers and typical readers of the same age, but not to

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1 typical readers of the same reading level. In contrast, DYS-A children showed no impairment  
2 in interval awareness compared to the controls. In addition, interval awareness performance  
3 was age sensitive, with CA controls performing better than RL controls. These analyses are  
4 presented in detail in Supplementary Material S4.4.

5 For notes, the ANOVA revealed a main effect of group,  $F(3,75) = 3.58, p = .018, \eta^2_p =$   
6  $.125$ , but no significant main effect of condition ( $F < 1$ ) or interaction ( $F = 1.52, p = .216$ ). Post-  
7 hoc analyses indicated impaired note awareness in DYS+A children compared to typical  
8 readers of the same age, but not to their DYS-A peers nor to typical readers of the same reading  
9 level. In contrast, DYS-A children showed no impairment in note awareness compared to the  
10 controls. In addition, note awareness performance was not age sensitive, with CA controls  
11 performing not significantly different from RL controls. These analyses are presented in detail  
12 in Supplementary Material S4.5.

13 For timbres, the ANOVA revealed main effects of condition,  $F(1,75) = 27.10, p < .001,$   
14  $\eta^2_p = .265$ , and group,  $F(3,75) = 4.42, p = .003, \eta^2_p = .172$ , but no significant interaction ( $F =$   
15  $1.12, p = .345$ ). Post-hoc comparisons indicated impaired timbre processing in DYS+A children  
16 compared to both their DYS-A peers and typical readers of the same age, but not to typical  
17 readers of the same reading level. In contrast, DYS-A children showed no impairment in timbre  
18 processing compared to the controls. In addition, it can be noted that timbre performance was  
19 not age sensitive, with CA controls performing not significantly different from RL controls.  
20 These analyses are presented in detail in Supplementary Material S4.6.

### 21 *Auditory Attention*

22 To explore the potential role of auditory attention in the comorbidity between dyslexia  
23 and amusia, a 3 (Material: word, pitch, timbre) x 2 (Level of difficulty, henceforth Level: target  
24 to be identified among 1 vs. 3 types of distractors) x 4 (Group: DYS+A children, DYS-A  
25 children, CA controls, RL controls) mixed-design ANOVA was computed on the  $d'$  sensitivity

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1 index, with material and level as within-participant factors and group as between-participants  
2 factor. The outcomes of this analysis are summarized in Table 3 and average  $d'$  values are  
3 shown in Figure 5.

4 *- Insert Figure 5 here -*

5 The ANOVA revealed significant main effects of level,  $F(1, 76) = 234.07, p < .001, \eta^2_p =$   
6  $.755$ , and group,  $F(3, 76) = 11.81, p < .001, \eta^2_p = .318$ , and a significant interaction between  
7 material and level,  $F(2, 152) = 21.51, p < .001, \eta^2_p = .221$ , but no other significant main effect  
8 or interaction (all  $F_s < 1$  except for Material x Level x Group:  $F(6, 152) = 1.67, p = .133$ )<sup>5</sup>.  
9 Importantly, the interaction between material and group was not significant, nor was the higher-  
10 order interaction including these two factors. This was confirmed by a 3 (Material) x 2 (Level)  
11 x 4 (Group) Bayesian mixed-design ANOVA on  $d'$ . An analysis of specific effects showed a  
12 high  $BF_{\text{exclusion}}$  score for the interaction between material and group ( $BF_{\text{exclusion}} = 36.6$ ),  
13 providing strong (Raftery, 1995) or very strong (Jeffreys, 1961) evidence in favor of the  
14 absence of such interaction.

15 Regarding the interaction between material and level, it was mainly due to a particularly  
16 strong difference in salience for timbres between levels 1 and 2, compared to the other materials  
17 (see detailed results in Supplementary Material S5.1). Regarding the main effect of group, post-  
18 hoc comparisons indicated impaired auditory attention in DYS+A children compared to both  
19 their DYS-A peers and typical readers of the same age, but not to typical readers of the same  
20 reading level. In contrast, DYS-A children showed no impairment in auditory attention  
21 compared to the other groups. In addition, auditory attention performance was age sensitive,

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<sup>5</sup> When the two DYS+A children with ADD were removed from the analyses, the results remained similar, with significant main effects of level,  $F(1, 74) = 231.76, p < .001, \eta^2_p = .758$ , and group,  $F(3, 74) = 10.91, p < .001, \eta^2_p = .307$ , and a significant interaction between material and level,  $F(2, 148) = 23.55, p < .001, \eta^2_p = .241$ , but no other significant main effect or interaction (all  $F_s < 1$ ).



1 with CA controls performing better than RL controls. These analyses are presented in detail in  
2 Supplementary Material S5.2.

### 3 ***Summary of Key Group Differences across Tasks***

4 Table 3 summarizes the significant main effects and interactions involving the group  
5 factor in the ANOVAs and corresponding post-hoc analyses for each task of the experimental  
6 battery. Of the three investigated functions (auditory STM, perceptual awareness, and  
7 attention), only auditory serial-order STM revealed the pattern of group differences that might  
8 indicate a core impairment common to dyslexia and amusia: namely, for short- and medium-  
9 length auditory sequences, DYS+A children performed significantly worse than both CA and  
10 RL controls. This impairment was expressed independently of material and regardless of the  
11 lower pitch discrimination skills of DYS+A children. The auditory item STM, perceptual  
12 awareness, and attention tasks also revealed impairments in the DYS+A children, but only in  
13 comparison to CA controls. In contrast, DYS-A children did not show impairment in any of the  
14 tasks.

15 *- Insert Table 3 here -*

### 16 **Individual Profiles**

17 Beyond the group effects reported above, the purpose of the following analyses was to  
18 examine individual profiles to determine whether children with dyslexia were consistently  
19 impaired across all tests. Of particular interest was the case of the 15 DYS+A children. To limit  
20 the number of comparisons, for each task,  $d'$  sensitivity indexes were first averaged across  
21 conditions, materials, lengths, and/or levels based on the results of the ANOVAs presented in  
22 Table 3. We selected only those factors for which group differences emerged significantly in  
23 the post-hoc comparisons, resulting in a total of 11 composite variables (i.e., for the auditory  
24 STM tasks: word, pitch, item, order length 3, and order length 4 performance; for the auditory  
25 perceptual awareness tasks: phoneme, syllable, interval, note, and timbre performance; for the

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1 auditory attention tasks: overall performance; see Table 3 for an overview). For each composite  
2 variable, participants' performance was transformed into two standardized z-scores: one was  
3 calculated by reference to the mean and standard deviation of the CA controls, the other by  
4 reference to the mean and standard deviation of the RL controls<sup>6</sup>. We then examined the  
5 proportion of participants scoring significantly below the norm in each group and for each  
6 variable. Any z-score falling below a threshold of -1.65 (i.e., below the 5<sup>th</sup> percentile of a normal  
7 distribution) relative to both CA and RL controls was considered as reflecting deviant  
8 performance.

9 Table 4 summarizes the number of participants showing deviant performance for each  
10 variable. As indicated by chi-square tests, a higher proportion of DYS+A children had deviant  
11 performance for pitch STM compared to CA controls, for order length 3 STM compared to  
12 DYS-A children, CA controls, and RL controls, and for order level 2 STM compared to CA  
13 and RL controls. No other significant group difference was observed.

14 Table 5 shows the individual performance profiles of the dyslexic children. Among the  
15 15 DYS+A children, two did not show any deviant score, three showed a specific impairment  
16 for one variable (one for order length 3 STM, one for order length 4 STM, and one for note  
17 awareness), and all others showed deviant scores for multiple variables. Among the 15 DYS-A  
18 children, two showed a specific impairment for one variable (one for order length 3 STM and  
19 one for order length 4 STM), two showed deviant scores for multiple variables (one for pitch  
20 STM and order length 4 STM, and one for word STM and syllable awareness), and all others  
21 did not show any deviant score. Overall, despite considerable heterogeneity in individual

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<sup>6</sup> Note that the mean and SD used for z-score calculation was computed after removing the CA and RL participants with extreme performance (i.e.,  $z > 1.65$  and  $z < -1.65$ , relative to the distribution of their respective groups), but that these extreme performers were still included in the following analyses.

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1 profiles, auditory serial-order STM stood out as the most convincing candidate to explain the  
2 comorbidity between dyslexia and amusia.

3 *- Insert Table 4 here -*

4 *- Insert Table 5 here -*

### 5 **Relationships Between Reading Level, Music Perception Skills and Tasks Performance**

6 We computed correlations between the *MIM index* (calculated by dividing the MIM  
7 reading score by the MIM reading time), MBEMA global score, and participants' performance  
8 as represented by our 11 composite variables. Several positive correlations, both within and  
9 between domains, were significant across the four groups of participants after partialing out  
10 potential confounding factors such as age, parents' SES, music education, and nonverbal  
11 intelligence. In particular, we observed moderate to strong positive correlations between  
12 participants' order STM performance, reading level, and music perception skills. However,  
13 almost none of them reached significance when carried out by group (see Supplementary  
14 Material S6 for detailed results). Given the number of participants in each group, it is difficult  
15 to determine whether the absence of significant within-group correlations was due to a lack of  
16 statistical power, or whether the correlations observed across all participants merely reflected  
17 group differences, without a general relationship.

### 18 **Discussion**

19 The present experiment aimed at testing the hypothesis that developmental dyslexia and  
20 congenital amusia might share common underlying cognitive impairment(s), which may  
21 explain the observation of substantial comorbidity between these two developmental disorders  
22 (Couvignou et al., 2019; Couvignou & Kolinsky, 2021). For this purpose, we designed a set of  
23 auditory behavioural tasks assessing short-term memory (STM), perceptual awareness, and  
24 attention skills for words, pitches, and timbres. These tasks were administered to dyslexic  
25 children with amusia (DYS+A), dyslexic children without amusia (DYS-A), as well as to two

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1 groups of typically developing children matched to the dyslexic children on either  
2 chronological age (CA) or reading level (RL).

3 Overall, our results suggest that, of the underlying functions considered in the present  
4 work, only poor auditory serial-order STM increases susceptibility for comorbidity between  
5 dyslexia and amusia and may play a causal role in the development of the comorbid phenotype.  
6 The impairments in auditory item STM, auditory perceptual awareness, and auditory attention  
7 observed in the DYS+A children, in contrast, may be a consequence of their reduced reading  
8 experience combined with weaker musical skills, rather than a core impairment inherent to both  
9 disorders. Comparisons of performance between the DYS+A and DYS-A children suggest that  
10 the latter are more resourceful and/or have more effective compensatory strategies, or that their  
11 phenotype results from a different developmental trajectory.

12 We will first review the evidence our data provide for and against the hypothesis of  
13 common underlying impairment(s) between dyslexia and amusia. We will then discuss how  
14 these findings are of interest for delving into the aetiology of these two developmental disorders  
15 and for theoretical models of STM. Finally, after discussing some of the limitations of this  
16 study, we will address its implication for future research and practices.

### 17 **Are Dyslexia and Amusia Different Manifestations of Similar Underlying Impairment(s)?**

18 Assuming that dyslexia and amusia share common underlying impairment(s), we  
19 expected that (1) children with dyslexia would show a marked impairment in one or several of  
20 the specific functions examined, manifesting itself in both the DYS+A and DYS-A children in  
21 the verbal domain and being more pronounced in DYS+A children in the musical domain, (2)  
22 this impairment would be observed independently of reading experience and thus be revealed  
23 relative to both the CA and the RL control groups, (3) this impairment would affect most  
24 individual cases, and (4) participants' performance in the impaired function(s) would be  
25 positively correlated with their reading/musical performance.

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1           We will examine, for each of the three functions investigated here, how consistent our  
2 data are with these predictions. Regarding auditory STM, an important issue was the distinction  
3 between item-based and serial order-based retention processes. On item memory, the DYS+A  
4 children performed significantly worse than the CA controls but not significantly different from  
5 the RL controls, regardless of the material and length of the to-be-remembered sequence. The  
6 reasoning that this result pattern reflects the single effect of reduced reading experience does  
7 not seem valid in this case, because DYS-A have comparable reading experience (approximated  
8 by equivalent reading level) as DYS+A but do not show the same item memory impairment.  
9 Rather, we suggest that the DYS+A children's item memory impairment is a consequence of  
10 their reduced reading experience combined with other characteristics that are specific to their  
11 condition, such as weaker musical skills. On serial order memory, in contrast, the DYS+A  
12 children performed significantly below both the CA and RL controls for short and medium  
13 sequences, regardless of the material. This suggests that serial-order STM impairment may play  
14 a causal role in the development of the comorbidity. Analysis of individual profiles were  
15 consistent with this hypothesis, with a large majority of DYS+A children (12 of 15) showing  
16 serial-order STM deviant performance relative to both the CA and RL controls, whereas such  
17 an impairment was poorly represented in the other groups. In line with these observations, we  
18 also observed moderate to strong positive correlations between participants' order STM  
19 performance, reading level, and music perception skills after partialing out potential  
20 confounding factors such as age, parents' SES, music education, and nonverbal intelligence.  
21 However, almost none of these correlations reached significance when carried out by group,  
22 which may either be due to insufficient sample size or suggest the absence of a general  
23 relationship.

24           Regarding auditory perceptual awareness and auditory attention, the DYS+A children  
25 performed worse than the CA controls, but not significantly different from the RL controls,

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1 regardless of the material. Again, as the DYS-A children did not exhibit the same impairments,  
2 these probably result from the combined effects of DYS+A children's reduced reading  
3 experience and weaker musical skills. Analyses of individual profiles confirmed that the  
4 proportion of participants with deviant performance on these tasks relative to both the CA and  
5 RL controls was not significantly different between the DYS+A children and the other groups.  
6 Finally, music perceptual awareness performance (i.e., awareness of intervals, notes, and  
7 timbres, but not of syllables or phonemes) correlated moderately with music perception  
8 performance, but not with reading performance. Auditory attention performance correlated  
9 moderately with both reading and music perception performance.

10 Overall, of the cognitive functions investigated in the present study, auditory serial-  
11 order STM verified almost all our predictions and appears to be the strongest candidate to  
12 explain the comorbidity between dyslexia and amusia. As we shall see, however, the absence  
13 of a clear impairment in the DYS-A children and the lack of a group of children with pure  
14 amusia do not allow us to conclude decisively about the role of this function in the aetiology of  
15 dyslexia and amusia separately. Therefore, our data do not provide a complete answer to the  
16 search for common underlying impairments between the two disorders. Impairments in auditory  
17 item STM, auditory perceptual awareness, and auditory attention were also associated with the  
18 comorbid phenotype, but they may merely be a consequence of the reduced reading experience  
19 inherent to dyslexia combined with weaker musical skills and are less likely to play a causal  
20 role in its development.

21 With regards to the potential underlying neural substrates, a set of neuroimaging studies  
22 conducted in adults and typically developing children have identified a right frontoparietal  
23 network centered on the intraparietal sulcus specifically associated with serial-order STM  
24 performance (Attout et al., 2019; Henson et al., 2000; Majerus et al., 2010; Marshuetz et al.,  
25 2006). Consistently, serial-order STM impairments in dyslexia have been associated with

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1 abnormal activation in a network encompassing the right intraparietal sulcus and superior  
2 frontal gyrus, in both the verbal and the visual domains. In amusia, the neural correlates of  
3 serial-order STM processes have rarely been studied to date, with the majority of imaging  
4 studies using paradigms that maximize item STM (Albouy, Mattout, et al., 2013; Albouy et al.,  
5 2015, 2019a). Only a transcranial alternating current stimulation study showed that modulation  
6 of the right dorsolateral prefrontal cortex selectively enhanced pitch serial-order STM in  
7 amusia, suggesting a causal involvement of this region for this ability (Schaal et al., 2015).  
8 These findings, combined with our observation of a serial-order STM impairment in DYS+A  
9 children, calls for an investigation of the neural correlate of the comorbidity between dyslexia  
10 and amusia, with the hypothesis that it might be related to the presence of dysfunctional  
11 networks in the right intraparietal sulcus or in the right dorsolateral prefrontal regions.

### 12 **Variability in Individual Profiles**

13 Although our data converge towards a role of auditory serial-order STM in explaining  
14 the substantial comorbidity rate between dyslexia and amusia, we also observed strong  
15 variability in the expression of this impairment across dyslexic participants. In particular, as a  
16 group, the DYS-A children did not show significant impairments in any of the experimental  
17 tasks. Although average results suggest that DYS-A children slightly underperform both the  
18 CA and RL controls in serial-order STM tasks for medium word sequences, at the individual  
19 level only a minor proportion of DYS-A children (3 of 15) showed deviant performance on the  
20 auditory serial-order STM task relative to both the CA and RL controls. One might wonder why  
21 they do not show such an impairment more clearly, at least for the verbal material, whilst the  
22 severity of their reading impairments is equivalent to those of the DYS+A children.

23 Several hypotheses can be considered in this regard. First, it could be that the DYS-A  
24 children do have such an auditory serial-order STM impairment, but that it is masked by the  
25 fact that they are more resourceful and/or have more effective compensatory strategies. In

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1 agreement with this hypothesis, the DYS-A group showed a slightly (although not significantly)  
2 higher nonverbal IQ and better auditory attentional skills than the DYS+A children. These  
3 differences, however, should be viewed with caution, as working memory capacity is also a  
4 strong predictor of fluid intelligence (Conway et al., 2002; Gray et al., 2017; Jaeggi et al., 2008)  
5 and has been shown to mediate the relationship between attention and intelligence scores  
6 (Cochrane et al., 2019). Thus, another potential interpretation of these group differences in  
7 nonverbal IQ and attention is that they are driven by the DYS+A children's STM impairment.

8         Conversely, one might think that the DYS+A children's pitch processing impairment  
9 exacerbates their phonological deficit, so that their impairments are more salient than those of  
10 DYS-A children and only these are detected by the battery. Indeed, very fine spectral and  
11 temporal differences (in particular, formants frequencies for vowels, and either voice onset time  
12 (VOT) or the frequencies of formant transitions for stop consonants) can lead to the perception  
13 of different phonemes. As Sun et al. (2017) argued, an impairment in the early stage of auditory  
14 processing may have a cascading effect on later stages, regardless of domain, and affect both  
15 musical and phonological processing. Our own data are not consistent with this hypothesis,  
16 because, overall, the reading and phonological performances of the DYS+A children were not  
17 statistically different from those of the DYS-A children despite their weaker pitch  
18 discrimination abilities. In fact, among the set of reading and phonological tasks, the DYS+A  
19 children performed slightly lower than the DYS-A in the pseudoword repetition task only,  
20 which probably reflects their auditory STM impairment.

21         Finally, it may be that the DYS+A and DYS-A children belong to two subtypes of  
22 dyslexia resulting from two different developmental trajectories, or at least that the reading  
23 difficulties of a significant number of children in the DYS-A group are primarily due to factors  
24 other than an auditory serial-order STM impairment. In particular, a number of children in the  
25 DYS-A group may have a reduced visual attention span, which has been suggested as an



1 alternative core impairment in developmental dyslexia (Bosse et al., 2007; Valdois et al., 2004).  
2 This hypothesis seems quite unlikely, however, given the moderate prevalence of such disorder  
3 in the dyslexic population and its limited power to explain reading difficulties beyond the  
4 phonological deficit (Saksida et al., 2016). In this regard, it should be noted that the DYS-A  
5 children did show a phonological deficit compared to the CA controls, as assessed by standard  
6 phonological tests (i.e., pseudoword repetition, initial syllable/phoneme deletion, and RAN).

### 7 **Poor Serial-Order STM as a Common Risk Factor for Learning Disorders?**

8 More broadly, and despite these individual disparities, our results are consistent with  
9 the hypothesis that auditory serial-order STM is a common risk factor for learning disorders,  
10 rather than a causally unrelated associated impairment. Note that by “risk factor” we do not  
11 mean that a serial-order STM impairment is a unique causal factor for all learning disorder  
12 profiles, but rather that its presence is likely to increase the probability of developing one or  
13 more of these disorders and to lead to comorbid phenotypes. In recent years, this hypothesis  
14 has received increasing support, with several studies pointing to serial-order STM impairments  
15 in dyslexia (Cowan et al., 2017; Majerus & Cowan, 2016; but see also Staels & Van den Broeck,  
16 2014, 2015) and dyscalculia (Attout & Majerus, 2015; De Visscher et al., 2015; Morsanyi et  
17 al., 2018) while highlighting the likely heterogeneity of these populations with respect to the  
18 presence and severity of these impairments. Yet, only a small number of studies addressed this  
19 issue in children (Attout & Majerus, 2015; Cowan et al., 2017; Morsanyi et al., 2018; Perez et  
20 al., 2012; Staels & Van den Broeck, 2014, 2015) and even fewer of these included a reading-  
21 level matched control group (but see e.g., Perez et al., 2012, for an exception), leaving the  
22 interpretation of most group differences ambiguous. In addition, the available evidence comes  
23 exclusively from the study of pure cases, leaving unanswered the question of the role of serial-  
24 order STM in the development of comorbid profiles.

## SHARED IMPAIRMENTS IN DYSLEXIA AND AMUSIA?

1           Here, we extend previous findings (Cowan et al., 2017; Majerus & Cowan, 2016) by  
2 showing that such an impairment can be observed in dyslexia independently of reading  
3 experience, but predominantly in cases with comorbid amusia, pointing to this impairment as a  
4 potential origin of the frequent co-occurrence of these two disorders. As exposed in the  
5 Introduction, auditory STM impairments have been extensively investigated in amusic adults  
6 over the past decade (for reviews, see: Caclin & Tillmann, 2018; Tillmann, Levêque et al.,  
7 2016). Yet, little attention has been paid to the potential distinction between item and serial-  
8 order STM processing in this population. In fact, while the gold standard battery for diagnosing  
9 amusia (Peretz et al., 2003) and its child-friendly versions (Peretz et al., 2013, 2021) involve  
10 mostly item STM (at least in the melodic subtests), subsequent paradigms used to characterize  
11 the auditory STM impairment of amusic individuals were sometimes item-based (Albouy et al.,  
12 2015, 2016, 2019b; Albouy, Mattout, et al., 2013; Foxton, 2004) and sometimes serial order-  
13 based (Albouy, Schulze, et al., 2013; Gosselin et al., 2009; Marin et al., 2012; Schaal et al.,  
14 2015; Tillmann et al., 2009; Williamson & Stewart, 2010), with no clear rationale for choosing  
15 one or the other memory process (note however that item-based and serial order-based STM  
16 tasks lead to rather similar performance in non-amusic adults, Talamini et al., 2022). Taken  
17 together, these studies point to both item and serial-order auditory STM impairments in  
18 congenital amusia, but the fact that these two aspects have never been studied comparatively  
19 and only in adults leaves several questions open. Do the two types of impairments co-exist with  
20 equivalent prevalence? Does one causes/exacerbates the other? How do these two processes  
21 interact during development?

22           Our study is one of the few to investigate the cognitive characteristics of congenital  
23 amusia in children (Couvignou & Kolinsky, 2021; Lebrun et al., 2012; Mignault Goulet et al.,  
24 2012) and the first to suggest that the dissociation between item and serial-order STM processes  
25 might be relevant to the aetiology of this disorder. However, because the amusic children we

1 tested had comorbid dyslexia, it is difficult to draw specific conclusions. It would be worthwhile  
2 to investigate this issue in pure cases of amusia, using tasks that allow for a systematic  
3 comparison of item and serial-order STM processes such as those we have developed here. The  
4 investigation of potential specific brain networks involved, as has been done in dyslexia for  
5 verbal and visual material (Martinez Perez et al., 2015), may shed further light on the status of  
6 item and serial order STM in amusia.

### 7 **Implications for Theoretical Models of STM**

8         Beyond considerations related to the aetiology of learning disorders, our results further  
9 support that the distinction between item-based STM processes and serial-order STM processes  
10 is relevant in several auditory domains. Gorin et al. (2016) provided direct evidence for this  
11 hypothesis in healthy adults, by comparing the differential effects of time-based interfering  
12 tasks on item and serial-order processing in verbal and musical STM. Here, we show that the  
13 item/order dissociation might be already relevant in both language and music at an earlier stage  
14 of development, as impaired serial-order STM appears to alter the processing of both domains  
15 in children. As reviewed by Ordonez-Magro et al. (2020) in the verbal domain, such distinction  
16 is critical to understanding the relationships between STM and reading acquisition insofar as  
17 item and serial order information interact with linguistic representations in different ways.  
18 Specifically, whereas recall of item information appears to be directly influenced by existing  
19 linguistic knowledge (i.e., the quality of the phonological, lexical, and semantic  
20 representations), the recall of serial order information seems to be relatively independent of it  
21 (Binamé & Poncelet, 2016; Poirier et al., 2015; Poirier & Saint-Aubin, 1995; Saint-Aubin et  
22 al., 2005). On the same basis, one might speculate that music perception relies on distinct  
23 involvement of item and order processes, with item information more strongly determined by  
24 the quality of pitch representations than serial order information. The hypothesis of impaired  
25 access to relatively intact auditory representations in dyslexia and amusia (Boets, 2014; Boets

1 et al., 2013; Moreau et al., 2013; Peretz et al., 2009; Ramus & Szenkovits, 2008; Tillmann,  
2 Levêque et al., 2016), combined with the observation of a stronger impairment in order STM  
3 compared to item STM in DYS+A children in our sample, may be consistent with these  
4 considerations. Overall, whereas the relevance of the item/order dissociation is relatively well  
5 documented in the verbal domain, our data further strengthens the need for musical STM  
6 models to take this distinction into account.

7         Another related debate that our data could help to inform is that of the domain specificity  
8 of STM processes. With respect to the auditory modality, and in particular the issue of the  
9 relationship between language and music, the body of evidence from healthy subjects, brain-  
10 injured patients, and subjects with congenital amusia suggests a partial dichotomy of verbal and  
11 musical STM processes, which tend to be affected together but not in a systematic way (Caclin  
12 & Tillmann, 2018). Recent data point to similar developmental trajectories between these two  
13 processes during childhood (Ginzburg et al., 2022). In the present study, the impaired serial-  
14 order STM of DYS+A children was expressed independently of material (i.e., for words,  
15 pitches, and timbre), as revealed by the absence of interaction with this variable. This may  
16 support the argument that serial-order STM is governed by common processes in the verbal and  
17 musical domains, in line with previous studies that have shown similar hallmarks of serial-order  
18 effects in verbal and musical STM (Gorin, 2021; Gorin et al., 2018; see also Williamson et al.,  
19 2010). One proposal is that music and language serial-order processing possibly rely on  
20 common sequential processes. Indeed, a number of theoretical models of serial-order STM  
21 suggest that serial order information is encoded using time-based processes (Brown et al., 2000;  
22 Burgess & Hitch, 1999, 2006). More generally, it would be worthwhile to test whether the  
23 processes engaged in auditory modality can cover other sensory modalities, such as vision. This  
24 proposition has received some support (Bigelow & Poremba, 2012; Pillai & Yathiraj, 2017;  
25 Visscher et al., 2007) but deserves to be further investigated, especially in children.

### 1 **Clinical Perspectives**

2           Our results hold potential implications for clinical practice. First, the dissociation  
3 between item and order STM processes, observed in our sample as well as in a growing number  
4 of studies (e.g., Attout et al., 2019; Cowan et al., 2017; Majerus & Cowan, 2016), should prompt  
5 practitioners to assess these two abilities separately in children with learning disorders.  
6 Accordingly, while the use of a standard digit span task may be useful in providing insight into  
7 the general functioning of working memory, it does not accurately characterize the impairments  
8 at play in case of failure. Our data suggest that additional measures of item and order STM  
9 would provide a more specific picture of the child's difficulty profile, and thus allow for more  
10 targeted and effective care.

11           Furthermore, our results may be useful for the construction of early detection batteries  
12 for children at risk for learning disorders. Given the negative impact of these disorders on  
13 schooling and daily life (e.g., Aro et al., 2019; Livingston et al., 2018), early detection of  
14 children likely to develop such difficulties constitutes a major public health issue. Specifically,  
15 our data encourage the inclusion in these batteries of tasks assessing serial-order STM, which,  
16 as discussed above, appears to be a common risk factor for several learning disorders. They  
17 further suggest the interest of extending this type of task to several materials (not only to the  
18 verbal domain, but also to the musical domain) for a better detection of children at risk of  
19 comorbidity. One advantage of the tasks we have developed here is that they are not only easily  
20 understandable and potentially administrable before reading acquisition, but also highly  
21 comparable across materials and conditions, allowing for an accurate profile of children's  
22 strengths and weaknesses. The paradigm adopted here (same/different judgment tasks) also  
23 allows to bypass production, which is problematic in the musical domain.

24           The next step would be to design intervention programs to address the learning  
25 difficulties of these children, potentially including exercises focused on training serial-order

1 STM. However, longitudinal and training studies are first needed to properly test the causality  
2 hypothesis. Several longitudinal studies suggest an involvement of verbal STM in reading  
3 acquisition (Bogaerts et al., 2016; Martinez Perez et al., 2012; Ordonez Magro et al., 2020) and  
4 in numerical development (Attout et al., 2014) but, to our knowledge, none has directly  
5 investigated the potential benefits of serial memory training on these skills. In the musical  
6 domain, an attractive proposal could be to offer training programs centered around rhythmic  
7 perception and production, which solicit sequential processing and would thus potentially train  
8 serial-order STM. Several theoretical models support such far transfer effects between rhythm  
9 and speech (e.g., Fiveash et al., 2021; Goswami, 2011; Tierney & Kraus, 2014), or more  
10 generally, between music and speech (Besson et al., 2011; Moreno & Bidelman, 2014; Patel,  
11 2011, 2014), and some studies have suggested potential benefits of music practice on various  
12 phonological abilities in dyslexia, including phonological sensitivity and awareness, categorical  
13 perception, and pre-attentive perception of VOT (Flaugnacco et al., 2015; Frey et al., 2019;  
14 Habib et al., 2016; Zuk et al., 2018). Yet, the experimental evidence for a causal effect of music  
15 training on reading skills remains debatable, with the latest meta-analyses showing weak to  
16 moderate effects (Bigand & Tillmann, 2022; Gordon et al., 2015). We suggest that future  
17 training studies in this field would benefit from incorporating more sequencing-focused  
18 exercises into the proposed remediation program, which is often very general and does not  
19 allow for specific conclusions to be drawn about the cause of any observed improvement.

### 20 **Potential Limitations**

21 Our study presents several shortcomings, potentially limiting some of the conclusions  
22 that can be drawn from our data set. First, as the sample size might be considered as relatively  
23 small compared to the number of tests and comparisons performed, generalization of our results  
24 to the dyslexic population requires replication in larger cohorts. Second, we did not constitute  
25 a group of children with pure amusia, which is difficult as they are not detected by the school

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1 system and hence are hard to identify. The absence of this group constrains us to conjecture  
2 about congenital amusia from the DYS+A cases, which amounts to conceptualizing  
3 comorbidity as the simple addition of the two disorders without considering their probable  
4 interaction. Yet, comorbid individuals often differ in important ways from those with an  
5 isolated disorder, including greater symptom severity, more extensive and severe functional  
6 impairment, and poorer long-term outcomes (Willcutt et al., 2019). Future studies wishing to  
7 draw specific conclusions about the absence/presence of any of the disorders should benefit  
8 from the comparison of the three diagnostic categories (children with pure dyslexia, pure  
9 amusia, or presenting the comorbidity), although without neglecting the role of continuous  
10 measures of traits (e.g.,  $d'$  performance) in informing the effect of the degree of severity of the  
11 impairment on the development of these different cognitive profiles.

12 Third, it would have been desirable for the different groups to be matched on any social  
13 or cognitive characteristic (other than those inherent to dyslexia and amusia) that might  
14 influence their ability to perform the tasks. For example, we did not have precise information  
15 on the nature and duration of speech therapy received by the dyslexic participants, although it  
16 would have been relevant to match the DYS+A and DYS-A groups on these variables to avoid  
17 potential confounding influences. In a future study, these data should be collected and related  
18 to participants' performance or to the severity of their STM impairment. As discussed above,  
19 DYS+A children had slightly lower (though not significantly) non-verbal IQ than the other  
20 groups. Their pitch discrimination skills were also lower than those of the other children (Table  
21 2), which is consistent with the characteristics of impaired pitch processing in congenital  
22 amusia (Hyde & Peretz, 2004; Peretz et al., 2002). These differences may have influenced the  
23 performance pattern observed in the experimental tests, particularly for the pitch STM tasks  
24 (Jiang et al., 2013). We tried to control for this possibility by removing the trials involving  
25 musical intervals below the pitch discrimination threshold of each participant (which did not

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1 change the pattern of results), but we cannot completely rule it out. It should be noted, however,  
2 that the serial-order STM impairment of the DYS+A children was observed independently of  
3 material and therefore our main conclusion remains valid despite this limitation.

4         Several other weaknesses related to the construction of our experimental battery can be  
5 discussed, as well as its validity for measuring some of the cognitive functions studied. Notably,  
6 in the STM task, the item and order conditions were not perfectly matched in terms of difficulty  
7 for the pitch material, as the item condition involved larger interval changes than the order  
8 condition (Supplementary Material S1). These mismatches may have influenced our results for  
9 the pitch material, but do not alter the overall conclusion of the study relative to the serial-order  
10 STM of the DYS+A children, which was observed independently of material. Likewise, the  
11 verbal counterpart of the perceptual awareness task (syllable and phoneme perceptual  
12 awareness) did not correlate with reading measure, which is in contradiction with a large body  
13 of literature linking phonological awareness and reading performance (Swanson et al., 2003),  
14 and suggests that we might not have fully measured the intended skill. This is in line with the  
15 result showing that the DYS-A children did not present a clear impairment with phonemes in  
16 this task, even though phoneme awareness is considered one of the most consistent features of  
17 dyslexia. A notable difference between our experimental task and classical syllable/phoneme  
18 deletion tasks that have consistently shown deficits in dyslexia is that our task requires a simple  
19 identification of the correct answer without oral production. This choice was made to avoid  
20 singing production in the musical version of the task, because singing abilities are often  
21 impaired in children with comorbid dyslexia and amusia (Couvignou & Kolinsky, 2021) and  
22 difficult to apply to timbres, which we used as a control material. A consequence of this design,  
23 however, is that our task may have required less effort to access phonological information than  
24 classical deletion tasks. Specifically, it may be that such access is more accurately estimated in  
25 a “remember” rather than in a “know” paradigm, which requires the recall of items instead of



1 their recognition. Thus, the absence of group differences is not sufficient to rule out a role for  
2 perceptual awareness in the comorbidity between dyslexia and amusia.

3         Accordingly, it would be worth investigating further the issue of conscious access to  
4 auditory representations, including at the neurophysiological level, looking at the early and late  
5 components of auditory brain evoked potentials for both speech and music. In particular, if a  
6 delayed conscious access to fine auditory changes underlies comorbidity between the two  
7 disorders (Moreau et al., 2013; Neuhoff et al., 2012), the P3b component (associated with the  
8 conscious discrimination of targets in a sequence of repeated distractors; van Dinteren et al.,  
9 2014) but not the MMN (which reflects unattentive processing to changes in a continuous  
10 stream of identical sounds; Näätänen et al., 2007) should be impaired for both materials in  
11 comorbid individuals. Alternatively, if unattentive processing was affected, the MMN should  
12 also be affected. Although our experimental measures did not show any behavioral impairment  
13 in the DYS-A children, this type of neurophysiological investigation could help reveal a more  
14 subtle impairment in these individuals.

15         Finally, the conclusions that can be drawn from the current study are limited to the  
16 cognitive functions we have investigated. For feasibility concerns (the experimental battery  
17 being already demanding to administer to young children), we focused on the target domains  
18 of the two disorders (phonemes and pitch). However, it is quite possible that other dimensions  
19 play a role in the increased comorbidity. In particular, the role of the time dimension of music  
20 would be worth exploring (Fiveash et al., 2021). Impaired temporal processing has been  
21 reported in both dyslexia (e.g., Casini et al., 2018; Farmer & Klein, 1995; Goswami, 2011) and  
22 *tone deafness* amusia (Lagrois & Peretz, 2019), and a sizeable proportion of individuals with  
23 the comorbidity demonstrate difficulties in the *Rhythm* subtest of the MBEA/MBEMA,  
24 although difficulties with pitch processing prevail (Couvignou et al., 2019; Couvignou &

1 Kolinsky, 2021<sup>7</sup>). More generally, self-reported developmental disorders appear to be  
2 preferentially associated with time-based rather than pitch-based musical impairments (Peretz  
3 & Vuvan, 2017), and recent theoretical reviews have proposed rhythm difficulties as a common  
4 risk factor for developmental disorders, including developmental speech and language  
5 disorders (Ladányi et al., 2020; Lense et al., 2021). Temporal processing as in rhythm  
6 processing or even beat and meter, requires sequential capabilities. The auditory serial-order  
7 STM impairment revealed by the present study is likely based on such processes as well.  
8 Together, these considerations call for further exploration of rhythm processing in future studies  
9 aimed at unraveling the links between dyslexia and amusia.

### 10 **Concluding Remarks**

11 Overall, our results point to auditory serial-order STM as a plausible candidate to  
12 explain the shared variance and comorbidity between reading and music disorders. Despite its  
13 limitations, our study sheds new light on the currently underexplored relationship between  
14 dyslexia and amusia, and also on understanding the broader issue of comorbidities between  
15 learning disabilities. In addition, it contributes to a better theoretical understanding of auditory  
16 STM. Further research (in particular, longitudinal and training studies) will be needed to assert  
17 the potential causal role of this function in the aetiology of developmental disorders.

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<sup>7</sup> See also data from the present study, available under OSF: 10 of 15 DYS+A children performed below -2 SD on this subtest.

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### 11 **Disclosure statement**

12 The authors report no conflict of interest.

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Tables with caption

**Table 1**

*Demographic and Cognitive Characteristics of Participants as a Function of Group*

	Groups				Between-groups comparisons					
	DYS+A <i>n</i> = 15	DYS-A <i>n</i> = 15	CA <i>n</i> = 25	RL <i>n</i> = 25	DYS+A vs. DYS-A	DYS+A vs. CA	DYS+A vs. RL	DYS-A vs. CA	DYS-A vs. RL	CA vs. RL
Age (years)	10.6 (1.7)	10.4 (1.6)	10.7 (1.6)	8.3 (1.5)	0.18	-0.06	1.56***	-0.24	1.39***	1.64***
Sex <sup>a</sup>	8 F / 7 M	8 F / 7 M	14 F / 11 M	14 F / 11 M	.00	.03	.03	.03	.03	.00
Grade <sup>b</sup>	4.7 (1.7)	4.7 (1.5)	5.0 (1.7)	2.4 (1.5)	-0.04	-0.17	1.39***	-0.14	1.52***	1.56***
Music education (years)	0.7 (1.0)	0.6 (1.3)	0.7 (1.2)	0.6 (1.3)	0.01	-0.03	0.03	-0.04	0.01	0.05
Parents' SES <sup>c</sup>	65.3 (13.4)	69.9 (13.0)	73.6 (13.0)	66.8 (13.6)	-0.35	-0.63	-0.11	-0.28	0.23	0.51
Nonverbal IQ <sup>d</sup>	94.2 (10.3)	101.7 (15.1)	100.7 (12.8)	97.2 (12.9)	-0.58	-0.55	-0.25	0.07	0.32	0.28
Reading										
MIM score (/72) <sup>e</sup>	49.3 (11.0)	49.5 (16.7)	64.9 (3.5)	50.8 (15.3)	-0.01	-2.15***	-0.11	-1.46***	-0.08	1.27***
MIM time (s)	159.5 (89.3)	203.2 (168.5)	62.1 (11.8)	220.9 (196.3)	-0.32	1.77***	-0.37	1.37***	-0.10	-1.14***
Phonology										
Pseudoword repetition (/40)	24.1 (3.0)	26.7 (2.7)	29.5 (2.9)		-0.90*	-1.82***		-1.00**		
Initial S/P deletion (/42)	36.7 (3.8)	38.4 (3.8)	41.6 (0.7)		-0.46	-2.08***		-1.34***		
RAN (s) <sup>f</sup>	126.7 (23.7)	116.2 (27.3)	92.2 (19.1)		0.41	1.65***		1.07**		
MBEMA (/60) <sup>g</sup>	40.1	53.3	52.8	48.6	-2.56***	-2.98***	-1.66***	0.01	1.08**	1.14***

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(6.0) (4.0) (2.8) (4.5)

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*Note.* Group means are shown (standard deviations in parentheses). The last six columns present the results of group comparisons ( $\chi^2$  tests for sex ratio, *t*-tests showing Cohen's *d* for all other variables). DYS+A: dyslexic children with amusia, DYS-A: dyslexic children without amusia, CA: chronological-age matched controls, RL: reading-level matched controls.

<sup>a</sup> Sex ratio (F: Female, M: Male). <sup>b</sup> Mean grade was calculated using the following scale: 1<sup>st</sup> G (G: Grade) = 1, 2<sup>nd</sup> G = 2, 3<sup>rd</sup> G = 3, 4<sup>th</sup> G = 4, 5<sup>th</sup> G = 5, 6<sup>th</sup> Grade = 6, 7<sup>th</sup> G = 7, 8<sup>th</sup> G = 8. <sup>c</sup> Parents' socio-economic status (SES) was estimated by averaging their Index for Individual Socioeconomic Level (Genoud, 2011), calculated as follows: age – 6 x level of school completed – 4 x employment category + 55. An index of 55-67 corresponds to the middle class. An index of 68-80 corresponds to the upper middle class. <sup>d</sup> Nonverbal IQ is expressed as standardized score. <sup>e</sup> MIM = *Mécanisme d'Identification des Mots* subtest from the *Batterie d'Évaluation du Langage Écrit* (BELEC, Mousty et al., 1994). S/P = Syllable/Phoneme. <sup>f</sup> RAN = Rapid Automatized Naming. <sup>g</sup> MBEMA = *Montreal Battery of Evaluation of Musical Abilities* (Peretz et al., 2013).

\*  $p < .05$ . \*\*  $p < .01$ . \*\*\*  $p < .001$ .

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**Table 2**

*Discrimination Scores as a Function of Group and Material*

	Groups				Between-groups comparisons					
	DYS+A	DYS-A	CA	RL	DYS+A vs. DYS-A	DYS+A vs. CA	DYS+A vs. RL	DYS-A vs. CA	DYS-A vs. RL	CA vs. RL
Word (/6)	5.6 (0.6)	5.9 (0.4)	5.7 (0.5)	5.4 (0.8)	-0.21	-0.10	0.08	0.11	0.28	0.17
Pitch (/6)	4.2 (1.2)	5.1 (1.1)	5.2 (1.1)	4.8 (1.1)	-0.44*	-0.48**	-0.31	-0.02	0.16	0.20
Timbre (/6)	5.9 (0.3)	5.9 (0.4)	5.8 (0.5)	5.6 (0.6)	0.07	0.10	0.22	0.03	0.16	0.12

*Note.* Group means are shown (standard deviations in parentheses). The last six columns present the results of group comparisons (Mann-Whitney *U* tests showing Rank-Biserial correlation). DYS+A: dyslexic children with amusia, DYS-A: dyslexic children without amusia, CA: chronological-age matched controls, RL: reading-level matched controls.

\*  $p < .05$ . \*\*  $p < .01$ . \*\*\*  $p < .001$ .

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**Table 3**

*Summary of the Significant Effects and Interactions Involving the Group Factor in the Main ANOVAs and Corresponding Post-hoc Tests Conducted on the d' Sensitivity Index for Each Task of the Experimental Battery*

Task	Significant effects of or interactions with group	Group differences on	Post-hoc tests
Auditory short-term memory	Material x Group	Word	DYS+A < CA RL < CA
		Pitch	DYS+A < DYS-A DYS+A < CA RL < CA
		Timbre	n.s.
	Condition x Length x Group <sup>a</sup>	Item	DYS+A < CA RL < CA
		Order length 3	DYS+A < DYS-A <b>DYS+A &lt; CA</b> <b>DYS+A &lt; RL</b>
		Order length 4	<b>DYS+A &lt; CA</b> <b>DYS+A &lt; RL</b>
		Order length 5	n.s.
Auditory perceptual awareness	Condition x Material x Group <sup>b</sup>	Syllable	DYS+A < CA RL < CA
		Phoneme	DYS+A < CA
		Interval	DYS+A < DYS-A DYS+A < CA RL < CA
		Note	DYS+A < CA
		Timbre	DYS+A < DYS-A DYS+A < CA
Auditory attention	Group		DYS+A < DYS-A DYS+A < CA DYS-A > RL RL < CA

*Note.* DYS+A: dyslexic children with amusia, DYS-A: dyslexic children without amusia, CA: chronological-age matched controls, RL: reading-level matched controls. In bold: expected pattern if there was a causal underlying impairment. n.s. = no significant group difference.

<sup>a</sup> The Condition x Length x Group interaction is not decomposed by length for item condition, because the Length x Group interaction was not significant in this condition. <sup>b</sup> The Condition x

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Material x Group interaction is not decomposed by condition, because the Condition x Group interaction was not significant for any of the materials.

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**Table 4**

*Number of Individuals Performing Below the Threshold of -1.65 Standard Deviation Relative to both CA and RL Controls, for Each Composite Variable and Group*

Task	Composite variable	Groups				$\chi^2$					
		DYS+A <i>n</i> = 15	DYS-A <i>n</i> = 15	CA <i>n</i> = 25	RL <i>n</i> = 24 or 25 <sup>a</sup>	DYS+A vs. DYS-A	DYS+A vs. CA	DYS+A vs. RL	DYS-A vs. CA	DYS-A vs. RL	CA vs. RL
Auditory short-term memory	Word	3	1	2	1	0.29	0.38	1.09	0.22	0.16	0.00
	Pitch	4	1	0	2	0.96	<b>4.74*</b>	1.18	0.07	0.18	0.52
	Item	2	0	1	1	0.54	0.23	0.18	0.07	0.06	0.00
	Order length 3	11	1	1	4	<b>13.89***</b>	<b>18.29***</b>	<b>12.52***</b>	0.14	0.17	0.89
	Order length 4	7	2	2	1	2.54	<b>5.98*</b>	<b>7.79**</b>	0.00	0.18	0.00
Auditory perceptual awareness	Syllable	3	1	0	2	0.59	2.91	0.32	0.07	0.18	0.52
	Phoneme	0	0	0	1	0.00	0.03	0.08	0.00	0.06	0.00
	Interval	0	0	0	2	0.00	0.03	0.16	0.00	0.16	0.52
	Note	3	0	1	2	1.48	1.19	0.32	0.07	0.25	0.00
	Timbre	3	0	0	5	3.33	2.91	0.73	0.00	0.16	3.57
Auditory attention	Global	3	0	0	4	3.33	2.91	0.01	0.00	0.28	2.45

*Note.* DYS+A: dyslexic children with amusia, DYS-A: dyslexic children without amusia, CA: chronological-age matched controls, RL: reading-level matched controls. Yates' correction was applied if any frequency was less than 1, or if at least 20% of frequencies were less than 5. In bold: significant between-group differences.

<sup>a</sup> The performance of the two RL controls who probably did not understand some of the tasks was removed from the relevant analysis (i.e., *n* = 24 RL in the auditory short-term memory task; *n* = 24 RL in the auditory perceptual awareness tasks; *n* = 25 RL in the auditory attention task).

\* *p* < .05. \*\* *p* < .01. \*\*\* *p* < .001



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**Table 5**

*Individual Performance Profiles of Dyslexic Children With and Without Amusia for each Composite Variable*

(a)

Task	Composite variable	DYS+A <sup>a</sup>														
		S038	S040	S054	S055	S075	S077	S079	S081	S083 <sup>c</sup>	S090	S095	S096	S110 <sup>c</sup>	S119	S130
Auditory short-term memory	Word	✓	✗	~	✓	✗	✓	✓	✓	~	~	✓	~	✗	✓	✓
	Pitch	~	~	✓	✗	✓	~	~	~	~	✓	~	✗	✗	✗	✓
	Item	~	~	✓	~	~	~	~	✓	~	✓	~	✗	✗	~	✓
	Order length 3	✓	✗	✓	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✓
	Order length 4	✗	✓	✓	✗	✓	✓	✓	✗	✗	✓	✓	✗	✗	✗	✓
Auditory perceptual awareness	Syllable	~	✓	✓	~	~	~	✓	✓	✗	✗	✓	~	✗	✓	✓
	Phoneme	~	~	✓	✓	~	✓	✓	~	~	~	✓	~	~	✓	✓
	Interval	✓	✓	~	~	~	~	✓	~	~	✓	✓	~	~	✓	~
	Note	✓	✓	✓	~	✓	✓	✗	✓	✓	✗	✗	✓	✓	✓	✓
	Timbre	~	✓	✓	~	✗	~	✓	✓	✓	~	✓	~	✗	✗	✓
Auditory attention	Global	✓	~	✓	~	✗	~	✓	~	~	~	✓	✗	✗	~	~

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(b)

Task	Composite variable	DYS-A <sup>b</sup>														
		S039	S047	S048	S052	S053	S060	S070	S076	S078	S080	S109	S132	S134	S136	S137
Auditory short-term memory	Word	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	~	✗
	Pitch	✓	✓	~	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	~	~
	Item	~	✓	~	✓	✓	~	✓	✓	✓	✓	✓	✓	✓	~	~
	Order length 3	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Order length 4	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓	✓	✓
Auditory perceptual awareness	Syllable	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	~	✗
	Phoneme	~	✓	✓	✓	✓	~	✓	✓	✓	✓	✓	✓	✓	✓	✗
	Interval	✓	~	✓	~	✓	✓	~	✓	✓	~	✓	✓	✓	✓	✓
	Note	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	~
	Timbre	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	~
Auditory attention	Global	✓	✓	~	~	✓	~	~	~	~	✓	✓	✓	✓	✓	✓

*Note.* Individual performance profiles are shown (a) for DYS+A children, and (b) for DYS-A children. ✗: score below the threshold of -1.65 SD

relative to both CA and RL controls, considered deviant. ~: score below -1.65 SD relative to CA controls only. ✓: score above -1.65 SD relative to both CA and RL controls. DYS+A: dyslexic children with amusia, DYS-A: dyslexic children without amusia, CA: chronological-age matched controls, RL: reading-level matched controls.

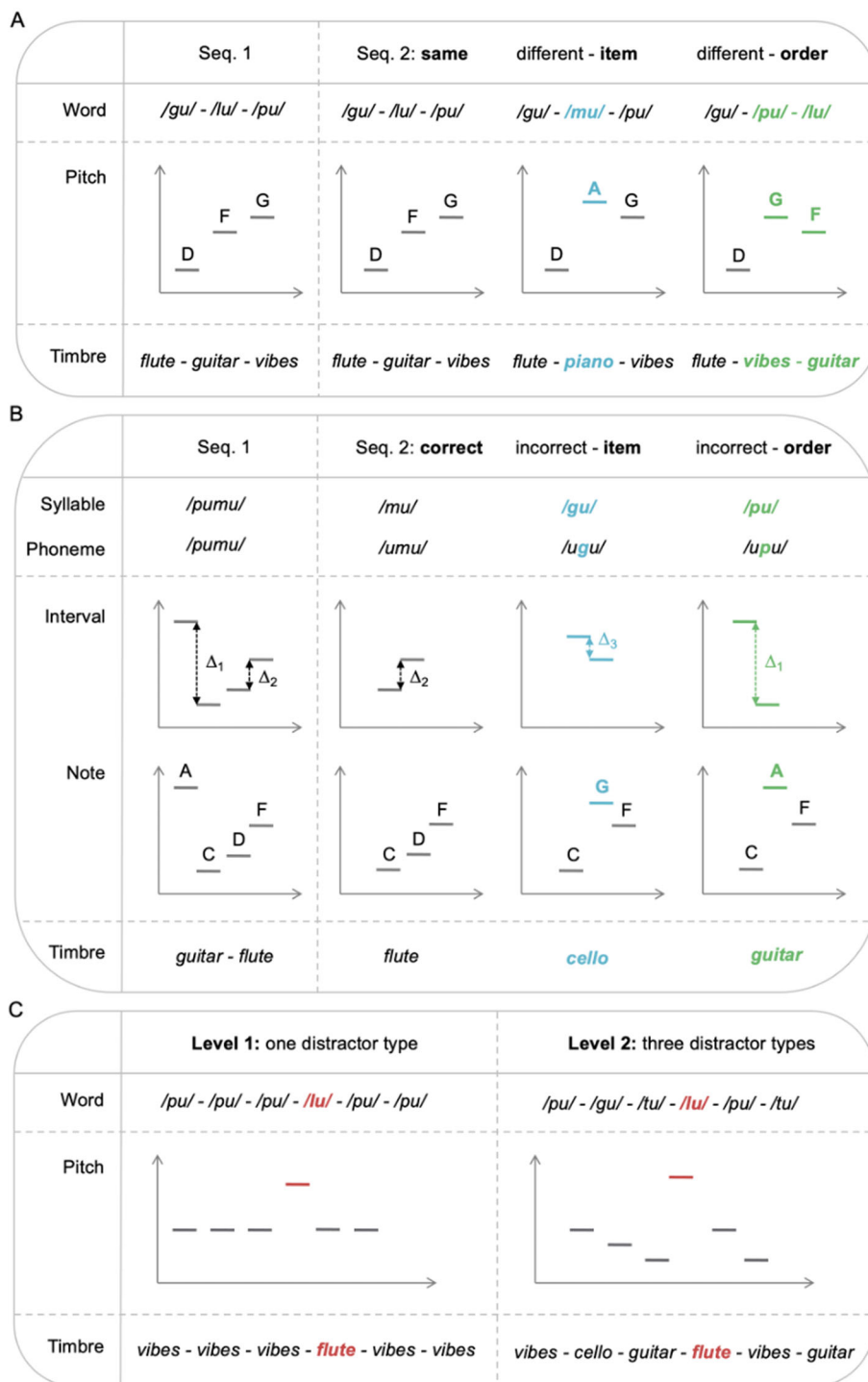
<sup>a</sup> Among the DYS+A children, S054 and S130 did not show any deviant score, S038, S077, and S079 showed a specific impairment for one variable, and all others showed deviant scores for multiple variables. <sup>b</sup> Among the DYS-A children, S048 and S109 showed a specific impairment for one variable, S060 and S137 showed deviant scores for multiple variables and all others did not show any deviant score. <sup>c</sup> S083 and S110 presented the triple comorbidity dyslexia, amusia, and ADD. As can be seen, S083 performance profile is not fundamentally different from those of his DYS+A

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peers without ADD. S110 shows the most numerous and severe impairments, but his profile is comparable to S096, who nevertheless has no additional ADD diagnosis. We therefore included S083 and S110 in the analyses despite their additional diagnosis of ADD, thereby maximizing the sample size.

Figures

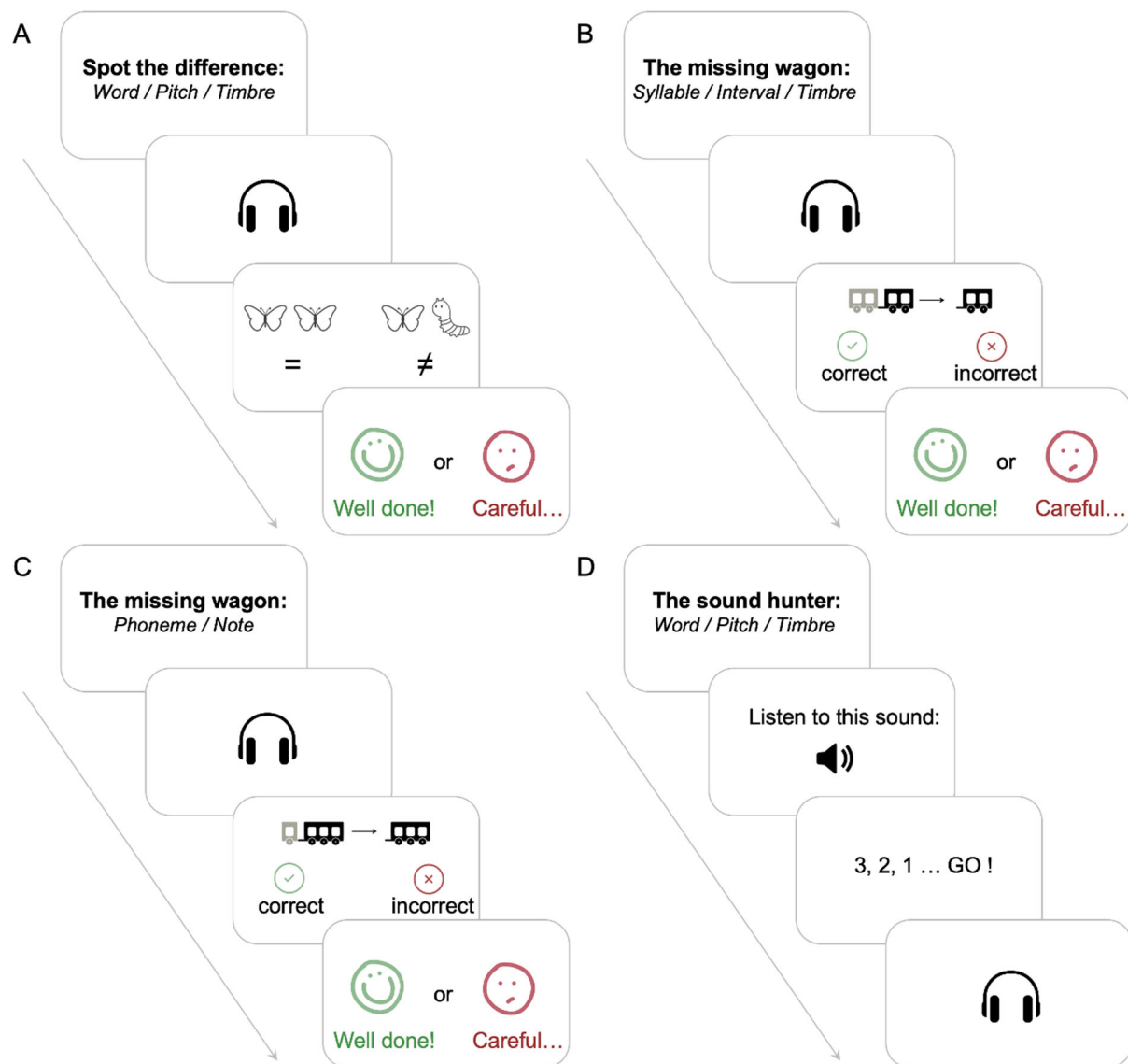
Figure 1



Note. (A) Short-term memory test (same/different judgment, here illustrated for length 3, with 3 items per sequence), (B) perceptual awareness test (correct/incorrect judgment), (C) attention test (go/no-go). The examples can be heard in Supplementary Material S7.

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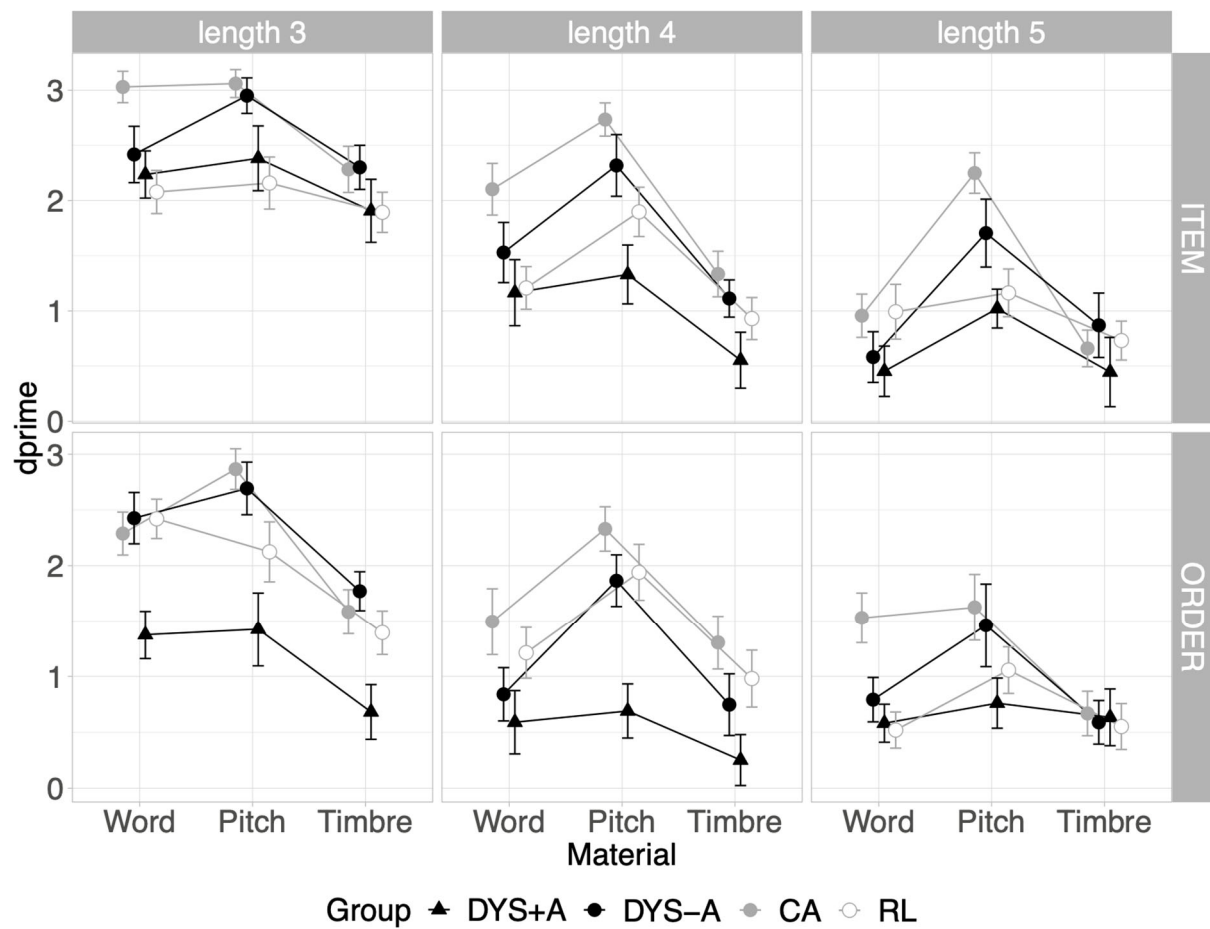
**Figure 2**



*Note.* (A) Short-term memory test, (B) syllable, interval, and timbre perceptual awareness tests, (C) phoneme and note perceptual awareness tests, (D) attention test. In tasks A-C, the children had to wait until the end of the stimuli presentation (illustrated on the screen by headphones) to give their answer, response choices being then illustrated on the screen. In task D, the target was first presented in isolation and then the test began after a visual countdown.

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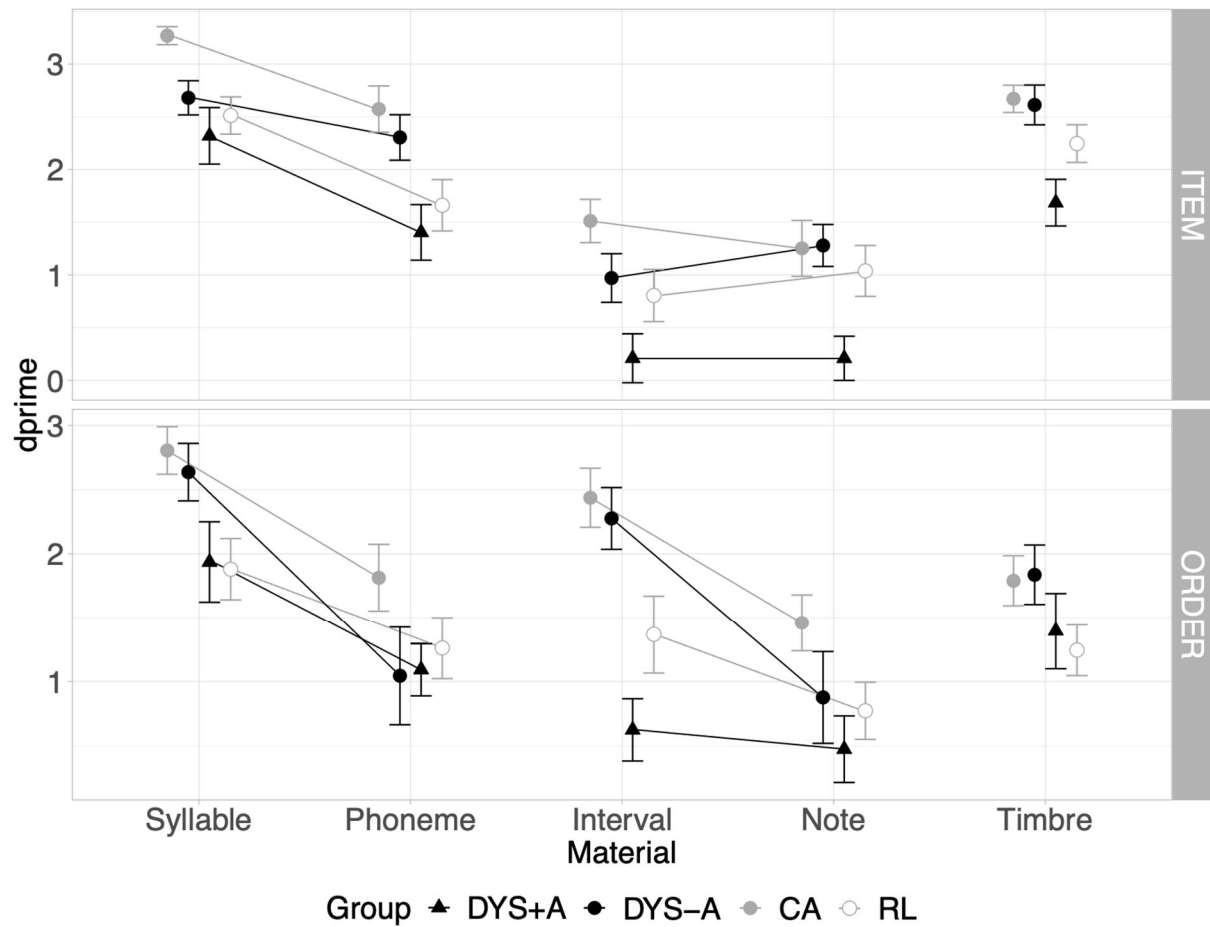
Figure 3



Note. Average  $d'$  values are shown. Error bars represent standard errors. DYS+A: dyslexic children with amusia, DYS-A: dyslexic children without amusia, CA: chronological-age matched controls, RL: reading-level matched controls.

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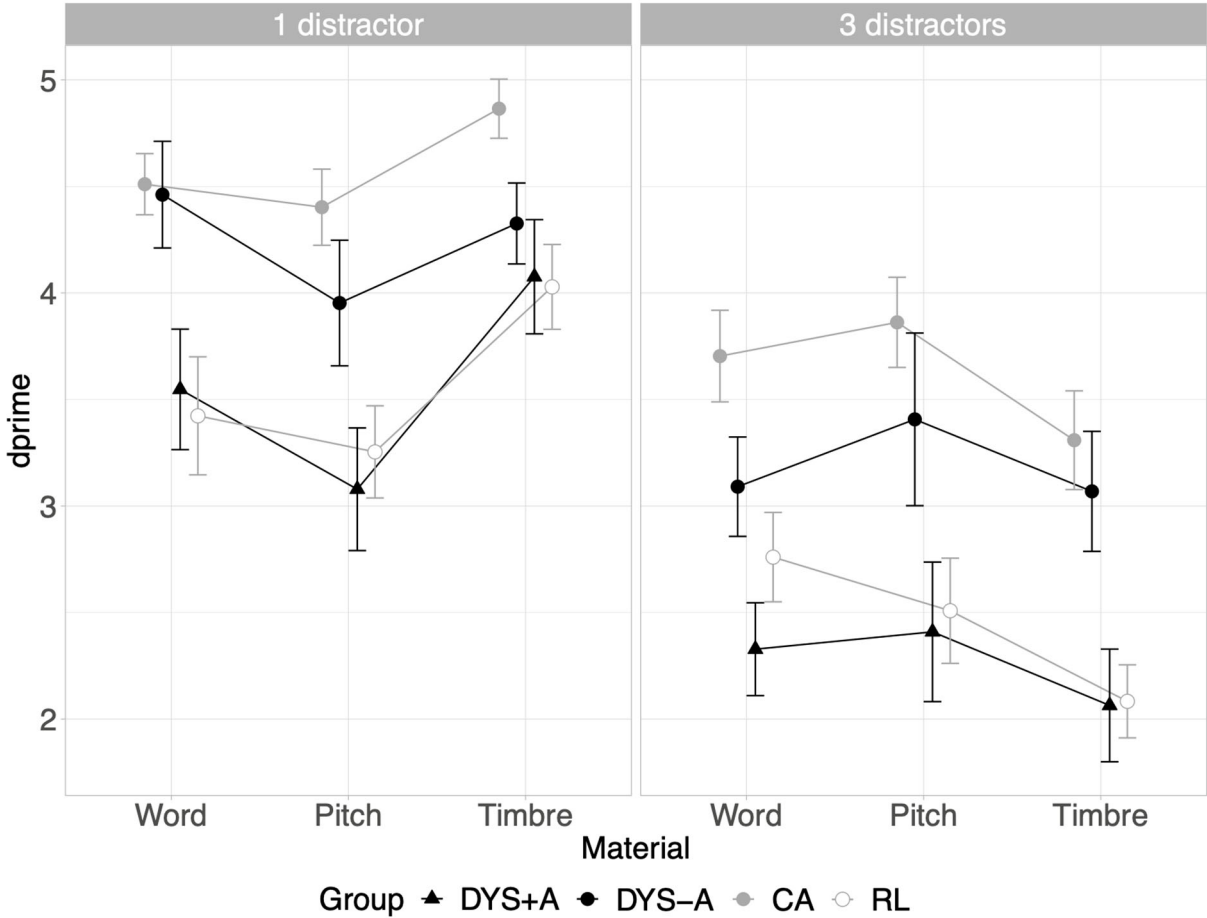
Figure 4



*Note.* Average  $d'$  values are shown. Error bars represent standard errors. DYS+A: dyslexic children with amusia, DYS-A: dyslexic children without amusia, CA: chronological-age matched controls, RL: reading-level matched controls.

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Figure 5



Note. Average  $d'$  values are shown. Error bars represent standard errors. **DYS+A**: dyslexic children with amusia, **DYS-A**: dyslexic children without amusia, **CA**: chronological-age matched controls, **RL**: reading-level matched controls.



**Figure captions**

**Figure 1**

*Schematic Illustration of the Materials and Tasks*

**Figure 2**

*Schematic Illustration of the Trials*

**Figure 3**

*Performance in the Auditory Short-term Memory Task as a Function of Group, Condition (Item, Order), Material, and Sequence Length (3, 4, or 5 Items per Sequence)*

**Figure 4**

*Performance in the Auditory Perceptual Awareness Task as a Function of Group, Condition (Item, Order), and Material*

**Figure 5**

*Performance in the Auditory Attention Task as a Function of Group and Level of Difficulty (Target to be Identified Among 1 vs. 3 Types of Distractors)*

**Supplementary Material S1****Control ANOVA on the Material used in the Auditory Short-term Memory Task**

In order to test whether changes in pitch were comparable between conditions and sequence length, two 2 (Condition: item, order) x 3 (Sequence length, henceforth Length: 3, 4, or 5 items per sequence), ANOVAs were conducted on the mean size of the interval change (in cents) and the mean number of contour changes, respectively. For the size of the interval change, the ANOVA revealed significant main effects of condition,  $F(1, 66) = 16.96, p < .001, \eta^2_p = .204$ , and length,  $F(2, 66) = 5.11, p = .009, \eta^2_p = .134$ , but no significant interaction ( $F < 1$ ). Regarding the main effect of condition, post-hoc comparisons using Bonferroni correction indicated that the mean size of the interval change was significantly larger in the item condition ( $M = 616.7$  cents,  $SD = 220.2$ ) than in the order condition ( $M = 419.4, SD = 220.2$ ),  $t(70) = 4.12, p < .001, d = 0.92, 95\% CI [101.6, 292.8]$ . Regarding the main effect of length, post-hoc comparisons using Bonferroni correction indicated that the mean size of the interval change was significantly larger for length 3 ( $M = 612.5, SD = 223.2$ ) than for length 4 ( $M = 425.0, SD = 206.9$ ),  $t(46) = 3.2, p = .006, d = 0.87, 95\% CI [46.9, 328.1]$ , but not significantly different from that for length 5 ( $M = 516.7, SD = 242.6$ ),  $t(46) = 1.63, p = .321$ , the latter being also not significantly different from that for length 4,  $t(46) = -1.56, p = .369$ . For the number of contour changes, the ANOVA revealed a significant main effect of length,  $F(2, 66) = 3.32, p = .042, \eta^2_p = .091$ , but no other significant main effect or interaction (all  $F$ s  $< 1$  except for condition:  $F(1, 66) = 1.78, p = .186$ ). Post-hoc comparisons using Bonferroni correction indicated that the mean number of contour changes for length 3 ( $M = 1.5, SD = 0.5$ ) was not significantly different from that for length 4 and 5 (respectively:  $M = 1.2, SD = 0.5, t(46) = 1.91, p = .182$ ;  $M = 1.5, SD = 0.6, t < 1$ ), but that the mean number of contour changes for length 4 tended to be significantly lower than that for length 5,  $t(46) = -2.45, p = .05, d = -0.70, 95\% CI [-0.7, 0.0]$ .

**Supplementary Material S2**

**Control ANOVA on the Material Used in the Auditory Perceptual Awareness Task**

In order to test whether changes in pitch were comparable between conditions and interval/note materials, two 2 (Condition: item, order) x 2 (Material: interval, note) ANOVAs were conducted on the mean size of the interval change (in cents) and the mean number of contour changes, respectively. For the size of the interval change, the ANOVA revealed a significant main effect of material,  $F(1, 44) = 15.97, p < .001, \eta^2_p = .266$ , but no other significant main effect or interaction (all  $F_s < 1$ ). Post-hoc comparisons using Bonferroni correction indicated that the mean size of the interval change was significantly lower for the interval ( $M = 216.7, SD = 149.4$ ) than for the note material ( $M = 450.0, SD = 237.7$ ),  $t(46) = -4.00, p < .001, d = -1.18, 95\% CI [-351.0, -115.7]$ . For the mean number of contour changes, however, the ANOVA revealed no significant main effect or interaction (all  $F_s < 1$  except for Condition x Material,  $F(1,44) = 3.43, p = .071$ ).

**Supplementary Material S3****Details of the ANOVA on  $d'$  for the Short-term Memory Task****Supplementary Material S3.1***Control Analysis for DYS+A Children's Lower Pitch Discrimination Skills*

To ensure that the lower pitch discrimination performance of DYS+A children (Table 2) did not influence the results, the analyses were repeated by removing, individually for each participant, trials involving pitch changes below their discrimination threshold. This threshold was estimated based on the results of the discrimination test, considering a threshold of 100 cents in case of failure on the trial involving a semitone difference, and a threshold of 200 cents in case of failure on both trials involving a one-tone difference. 2 DYS+A children, 1 DYS-A child, 2 CA controls, and 4 RL controls were considered to have a 100-cents threshold; 4 DYS+A children, 2 CA controls, and 2 RL controls were considered to have a 200-cents threshold. After removing the relevant trials (for a 100-cents threshold, 1 or 2 trials out of 216 depending on the set; for a 200-cents threshold, 5 or 6 trials out of 216 depending on the set), the pattern of results remained the same, with significant main effects of condition,  $F(1, 75) = 29.60, p < .001, \eta^2_p = .237$ , material,  $F(2, 150) = 55.32, p < .001, \eta^2_p = .424$ , length,  $F(2, 150) = 222.25, p < .001, \eta^2_p = .748$ , and group,  $F(3, 75) = 8.46, p < .001, \eta^2_p = .253$ , as well as significant interactions between condition and length,  $F(2, 150) = 7.25, p < .001, \eta^2_p = .088$ , material and length,  $F(4, 300) = 3.90, p = .004, \eta^2_p = .049$ , length and group,  $F(6, 150) = 2.60, p = .020, \eta^2_p = .094$ , and material and group,  $F(6, 150) = 2.57, p = .021, \eta^2_p = .093$ , and significant 3-way interactions between condition, material, and length,  $F(4, 300) = 3.41, p = .009, \eta^2_p = .044$ , and between condition, length, and group,  $F(6, 150) = 4.43, p < .001, \eta^2_p = .151$ . No other interaction was significant (all  $F_s < 1$  except for Condition x Group:  $F(3,75) = 1.79, p = .155$ , and Condition x Material x Length x Group:  $F(12, 300) = 1.52, p = .115$ ).

**Supplementary Material S3.2***Details of the Post-hoc Analyses for the Material\*Group Interaction*

Regarding the interaction between material and group, post-hoc comparisons using Bonferroni correction indicated that, for words, DYS+A children ( $M = 1.1$ ,  $SD = 1.1$ ) performed significantly worse than CA controls ( $M = 1.9$ ,  $SD = 1.3$ ),  $t(38)^1 = -3.81$ ,  $p = .004$ ,  $d = -0.43$ , 95% confidence interval (CI) [0.1, 1.6], but not significantly different from both DYS-A children ( $M = 1.4$ ,  $SD = 1.2$ ),  $t(28) = -1.49$ ,  $p = .273$ , and RL controls ( $M = 1.4$ ,  $SD = 1.2$ ),  $t(37) = -1.54$ ,  $p = .273$ . No other group difference was significant (all  $ps > .191$ ). For pitches, DYS+A children ( $M = 1.3$ ,  $SD = 1.1$ ) performed significantly worse than both DYS-A children ( $M = 2.2$ ,  $SD = 1.2$ ),  $t(28) = -3.67$ ,  $p = .006$ ,  $d = -0.41$ , 95% CI [-1.7, -0.1], and CA controls ( $M = 2.5$ ,  $SD = 1.1$ ),  $t(38) = -5.53$ ,  $p < .001$ ,  $d = -0.62$ , 95% CI [-2.0, -0.5], but not significantly different from RL controls ( $M = 1.7$ ,  $SD = 1.2$ ),  $t(37) = -2.07$ ,  $p = .273$ , the latter also performing significantly worse than CA controls,  $t(47) = -3.94$ ,  $p = .002$ ,  $d = -0.44$ , 95% CI [-1.4, -0.1]. No other group difference was significant (all  $ps > .273$ ). For timbres, no significant group-difference was observed (all  $ps < .273$ ).

**Supplementary Material S3.3***Details of the Post-hoc Analyses for the Condition\*Material\*Length Interaction*

The 3-way interaction between condition, material, and length was further investigated by performing three separate 2 (Condition: item, order) x 3 (Length: 3, 4, or 5 items per sequence) repeated measures ANOVAs on words, pitches, and timbres, averaging across groups. For words, the ANOVA revealed main effects of condition,  $F(1,78) = 6.09$ ,  $p = .016$ ,  $\eta^2_p = .072$ , and length,  $F(2,156) = 138.13$ ,  $p < .001$ ,  $\eta^2_p = .639$ , and a significant interaction

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<sup>1</sup> All  $t$ -tests reported in the present study are two-sided tests.

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between condition and length,  $F(2,156) = 4.80$ ,  $p = .009$ ,  $\eta^2_p = .058$ . Post-hoc comparisons using Bonferroni correction revealed that, for length 3, item performance ( $M = 2.5$ ,  $SD = 0.9$ ) was not significantly different from order performance ( $M = 2.2$ ,  $SD = 1.0$ ),  $t(78) = 2.20$ ,  $p = .086$ . In contrast, for length 4, item performance ( $M = 1.5$ ,  $SD = 1.1$ ) was significantly better than order performance ( $M = 1.1$ ,  $SD = 1.2$ ),  $t(78) = 3.24$ ,  $p = .004$ ,  $d = 0.37$ , 95% CI [0.0, 0.8]. For length 5, item performance ( $M = 0.8$ ,  $SD = 1.0$ ) was not significantly different from order performance ( $M = 0.9$ ,  $SD = 1.0$ ),  $t(78) < 1$ . For pitches, the ANOVA revealed main effects of condition,  $F(1,78) = 13.76$ ,  $p < .001$ ,  $\eta^2_p = .150$ , and length,  $F(2,156) = 56.82$ ,  $p < .001$ ,  $\eta^2_p = .421$ , but no significant interaction between condition and length ( $F < 1$ ). Regarding the main effect of condition, post-hoc comparisons using Bonferroni correction indicated that item performance ( $M = 2.1$ ,  $SD = 1.1$ ) was significantly better than order performance ( $M = 1.8$ ,  $SD = 1.3$ ),  $t(78) = 3.71$ ,  $p < .001$ ,  $d = 0.42$ , 95% CI [0.2, 0.5]. Regarding the main effect of length, post-hoc comparisons using Bonferroni correction indicated that performance at for length 3 ( $M = 2.5$ ,  $SD = 1.1$ ) was significantly better than performance for lengths 4 ( $M = 2.0$ ,  $SD = 1.1$ ),  $t(78) = 4.94$ ,  $p < .001$ ,  $d = 0.56$ , 95% CI [0.3, 0.8], and 5 ( $M = 1.4$ ,  $SD = 1.2$ ),  $t(78) = 9.30$ ,  $p < .001$ ,  $d = 1.05$ , 95% CI [0.8, 1.4] and that performance for length 4 was better than performance for length 5,  $t(78) = 7.08$ ,  $p < .001$ ,  $d = 0.80$ , 95% CI [0.4, 0.8]. For timbres, the ANOVA revealed main effects of condition,  $F(1,78) = 13.57$ ,  $p < .001$ ,  $\eta^2_p = .166$ , and length,  $F(2,156) = 50.47$ ,  $p < .001$ ,  $\eta^2_p = .427$ , and a significant interaction between condition and length,  $F(2,156) = 6.32$ ,  $p = .002$ ,  $\eta^2_p = .075$ . Post-hoc comparisons using Bonferroni correction revealed that, for length 3, item performance ( $M = 2.1$ ,  $SD = 1.0$ ) was significantly better than order performance ( $M = 1.4$ ,  $SD = 1.0$ ),  $t(78) = 5.13$ ,  $p < .001$ ,  $d = 0.58$ , 95% CI [0.3, 1.1]. In contrast, for length 4, item performance ( $M = 1.0$ ,  $SD = 1.0$ ) was not significantly different from order performance ( $M = 0.9$ ,  $SD = 1.2$ ),  $t(78) < 1$ . For length 5, item performance ( $M = 0.7$ ,  $SD = 1.0$ ) was not significantly different from order performance ( $M = 0.6$ ,  $SD = 0.9$ ),  $t(78) < 1$ .

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Overall, the difference in performance between item and order conditions was length dependent for words and timbres, but not for pitches (for which item performance was better than order performance for each length).

### **Supplementary Material S3.4**

#### *Details of the Post-hoc Analyses for the Main Effects of Length and Group in the Item Condition*

Regarding the main effect of length, post-hoc comparisons using Bonferroni correction indicated that performance for length 3 ( $M = 2.4$ ,  $SD = 0.7$ ) was significantly better than performances for lengths 4 ( $M = 1.6$ ,  $SD = 0.8$ ),  $t(78) = 12.67$ ,  $p < .001$ ,  $d = 1.43$ , 95% CI [0.7, 1.0], and 5 ( $M = 1.0$ ,  $SD = 0.7$ ),  $t(78) = 18.18$ ,  $p < .001$ ,  $d = 2.05$ , 95% CI [1.2, 1.6], and that performance for length 4 was significantly better than performance for length 5,  $t(78) = 6.80$ ,  $p < .001$ ,  $d = 0.77$ , 95% CI [0.4, 0.7]. Regarding the main effect of group, post-hoc comparisons using Bonferroni correction revealed that DYS+A children ( $M = 1.0$ ,  $SD = 0.7$ ) performed significantly worse than CA controls ( $M = 1.3$ ,  $SD = 0.6$ ),  $t(38) = -4.16$ ,  $p < .001$ ,  $d = -0.47$ , 95% CI [-1.3, -0.3], but not significantly different from both DYS-A children ( $M = 1.8$ ,  $SD = 0.5$ ),  $t(28) = -2.31$ ,  $p = .142$ , and RL controls ( $M = 1.5$ ,  $SD = 0.6$ ),  $t(37) = -.93$ ,  $p = 1.000$ , the latter also performing significantly worse than CA controls,  $t(47) = -3.68$ ,  $p = .003$ ,  $d = -0.41$ , 95% CI [-1.0, 0.2]. No other group difference was significant (all  $ps > .645$ ).

### **Supplementary Material S3.5**

#### *Details of the Post-hoc Analyses for the Length\*Group Interaction in the Order Condition*

Post-hoc comparisons using Bonferroni correction revealed that, for length 3, DYS+A children ( $M = 1.2$ ,  $SD = 0.7$ ) performed significantly worse than DYS-A ( $M = 2.3$ ,  $SD = 0.6$ ),  $t(28) = -4.09$ ,  $p = .001$ ,  $d = -0.46$ , 95% CI [-2.1, -0.2], CA controls ( $M = 2.3$ ,  $SD = 0.7$ ),  $t(38) =$

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-4.37,  $p = .001$ ,  $d = -0.49$ , 95% CI [-2.0, -0.2], and RL controls ( $M = 2.0$ ,  $SD = 0.8$ ),  $t(37) = -3.27$ ,  $p = .025$ ,  $d = -0.37$ , 95% CI [-1.7, 0.1], no other group difference being significant (all  $ps > .273$ ). For length 4, DYS+A children ( $M = 0.5$ ,  $SD = 0.7$ ) performed significantly worse than both CA controls ( $M = 1.7$ ,  $SD = 1.0$ ),  $t(38) = -4.82$ ,  $p < .001$ ,  $d = -0.54$ , 95% CI [-2.1, -0.3], and RL controls ( $M = 1.4$ ,  $SD = 0.8$ ),  $t(37) = -3.46$ ,  $p = .013$ ,  $d = -0.39$ , 95% CI [-1.7, -0.0], no other group difference being significant (all  $ps > .273$ ). In contrast, no group difference was significant for length 5 (all  $ps > .193$ ).



## Supplementary Material S4

### Details of the ANOVA on $d'$ for the Auditory Perceptual Awareness Task

#### Supplementary Material S4.1

##### *Control Analysis for DYS+A Children's Lower Pitch Discrimination Skills*

Similarly to the STM task, the pattern of results remained the same after removing trials involving pitch changes below each participant's discrimination threshold (for a 100-cents threshold, 8 or 13 trials out of 120 depending on the set; for a 200-cents threshold, 4 or 5 trials out of 120 depending on the set), with significant main effects of condition,  $F(1,75) = 8.49$ ,  $p = .002$ ,  $\eta^2_p = .120$ , material,  $F(4, 300) = 55.30$ ,  $p < .001$ ,  $\eta^2_p = .424$ , and group,  $F(3, 75) = 10.47$ ,  $p < .001$ ,  $\eta^2_p = .295$ , as well as a significant interaction between condition and material,  $F(4, 300) = 21.91$ ,  $p < .001$ ,  $\eta^2_p = .226$ , and a 3-way interaction between condition, material, and group,  $F(12, 300) = 1.86$ ,  $p = .039$ ,  $\eta^2_p = .069$ . No other interaction was significant (all  $F$ s  $< 1$  except for material x group:  $F(12, 300) = 1.15$ ,  $p = .318$ ).

#### Supplementary Material S4.2

##### *Details of the Post-hoc Analyses for the Main Effects of Condition and Group for Syllables*

Regarding the main effect of condition, post-hoc comparisons using Bonferroni correction indicated that item performance ( $M = 2.8$ ,  $SD = 0.8$ ) was significantly better than order performance ( $M = 2.3$ ,  $SD = 1.1$ ),  $t(78) = 3.31$ ,  $p = .001$ ,  $d = 0.37$ , 95% CI [0.2, 0.7]. Regarding the main effect of group, post-hoc comparisons using Bonferroni correction indicated that DYS+A children ( $M = 2.13$ ,  $SD = 1.13$ ) performed significantly worse than CA controls ( $M = 3.0$ ,  $SD = 0.8$ ),  $t(38) = -3.87$ ,  $p = .001$ ,  $d = -0.44$ , 95% CI [-1.6, -0.3], but not significantly different from both DYS-A children ( $M = 2.7$ ,  $SD = 0.7$ ),  $t(28) = -2.02$ ,  $p = .282$ , and RL controls ( $M = 2.2$ ,  $SD = 1.1$ ),  $t < 1$ , the latter also performing significantly worse than

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CA controls,  $t(47) = -4.09$ ,  $p < .001$ ,  $d = -0.46$ , 95% CI [-1.4, -0.3]. No other group difference was significant (all  $ps > .328$ ).

### Supplementary Material S4.3

#### *Details of the Post-hoc Analyses for the Main Effects of Condition and Group for Phonemes*

Regarding the main effect of condition, post-hoc comparisons using Bonferroni correction indicated that item performance ( $M = 2.0$ ,  $SD = 1.2$ ) was significantly better than order performance ( $M = 1.4$ ,  $SD = 1.2$ ),  $t(78) = 5.06$ ,  $p < .001$ ,  $d = 0.57$ , 95% CI [0.4, 0.9]. Regarding the main effect of group, post-hoc comparisons using Bonferroni correction indicated that DYS+A children ( $M = 1.3$ ,  $SD = 0.9$ ) performed significantly worse than CA controls ( $M = 2.2$ ,  $SD = 1.3$ ),  $t(38) = -2.89$ ,  $p = .030$ ,  $d = -0.33$ , 95% CI [-1.8, -0.1], but not significantly different from both DYS-A children ( $M = 1.7$ ,  $SD = 1.3$ ),  $t(28) = -1.17$ ,  $p = 1.000$ , and RL controls ( $M = 1.5$ ,  $SD = 1.2$ ),  $t(37) = -.65$ ,  $p = 1.000$ , the latter performing also not significantly different from CA controls,  $t(47) = -2.56$ ,  $p = .074$ . No other group difference was significant (all  $ps > .699$ ).

### Supplementary Material S4.4

#### *Details of the Post-hoc Analyses for the Main Effects of Condition and Group for Intervals*

Regarding the main effect of condition, post-hoc comparisons using Bonferroni correction indicated that item performance ( $M = 1.0$ ,  $SD = 1.1$ ) was significantly worse than order performance ( $M = 1.7$ ,  $SD = 1.4$ ),  $t(78) = -6.03$ ,  $p < .001$ ,  $d = -0.68$ , 95% CI [-1.1, -0.5]. Regarding the main effect of group, post-hoc comparisons using Bonferroni correction indicated that DYS+A children ( $M = 0.4$ ,  $SD = 0.9$ ) performed significantly worse than both DYS-A children ( $M = 1.6$ ,  $SD = 1.1$ ),  $t(28) = -3.43$ ,  $p = .006$ ,  $d = -0.39$ , 95% CI [-2.2, -0.3], and CA controls ( $M = 2.0$ ,  $SD = 1.9$ ),  $t(38) = -4.96$ ,  $p < .001$ ,  $d = -0.56$ , 95% CI [-2.4, -0.7], but not

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significantly different from RL controls ( $M = 1.1$ ,  $SD = 1.4$ ),  $t(37) = -2.11$ ,  $p = .227$ , the latter also performing significantly worse than CA controls,  $t(47) = -3.23$ ,  $p = .011$ ,  $d = -0.36$ , 95% CI [-1.6, -0.1]. No other group difference was significant (all  $ps > .564$ ).

### Supplementary Material S4.5

#### *Details of the Post-hoc Analyses for the Main Effects of Group for Notes*

Regarding the main effect of group, post-hoc analyses using Bonferroni correction indicated that DYS+A children ( $M = 0.3$ ,  $SD = 0.9$ ) performed significantly worse than CA controls ( $M = 1.4$ ,  $SD = 1.2$ ),  $t(38) = -3.23$ ,  $p = .011$ ,  $d = -0.36$ , 95% CI [-1.9, -0.2], no other group difference being significant (all  $ps > .235$ ).

### Supplementary Material S4.6

#### *Details of the Post-hoc Analyses for the Main Effects of Condition and Group for Timbres*

Regarding the main effect of condition, post-hoc comparisons using Bonferroni correction indicated that item performance ( $M = 2.3$ ,  $SD = 0.9$ ) was significantly better than order performance ( $M = 1.6$ ,  $SD = 1.0$ ),  $t(78) = 5.70$ ,  $p < .001$ ,  $d = 0.64$ , 95% CI [0.5, 1.1]. Regarding the main effect of group, post-hoc comparisons using Bonferroni correction indicated that DYS+A children ( $M = 1.5$ ,  $SD = 1.0$ ) performed significantly worse than both DYS-A children ( $M = 2.2$ ,  $SD = 0.9$ ),  $t(28) = -2.88$ ,  $p = .031$ ,  $d = -0.32$ , 95% CI [-1.3, 0.0], and CA controls ( $M = 2.2$ ,  $SD = 0.9$ ),  $t(38) = -3.24$ ,  $p = .011$ ,  $d = -0.37$ , 95% CI [-1.3, -0.1], but not significantly different from RL controls ( $M = 1.7$ ,  $SD = 1.0$ ),  $t < 1$ , the latter also performing not significantly different from CA controls,  $t(47) = -2.61$ ,  $p = .066$ . No other group difference was significant (all  $ps > .170$ ).

## Supplementary Material S5

### Details of the ANOVA on $d'$ for the Auditory Attention Task

#### Supplementary Material S5.1

##### *Details of the Post-hoc Analyses for the Material\*Level Interaction*

Regarding the interaction between material and level, post-hoc comparisons using Bonferroni correction indicated that, at level 1, word performance ( $M = 4.0$ ,  $SD = 1.2$ ) was not significantly different from pitch performance ( $M = 3.7$ ,  $SD = 1.2$ ),  $t(79) = 2.43$ ,  $p = .096$ , and not significantly different from timbre performance ( $M = 4.4$ ,  $SD = 0.9$ ),  $t(79) = -2.62$ ,  $p = .056$ , and pitch performance was significantly worse than timbre performance,  $t(79) = -5.04$ ,  $p < .001$ ,  $d = -0.56$ , 95% CI [-1.0, -0.3]. In contrast, at level 2, word performance ( $M = 3.0$ ,  $SD = 1.1$ ) was not significantly different from pitch performance ( $M = 3.1$ ,  $SD = 1.4$ ),  $t(79) = -.59$ ,  $p = .400$ , and not significantly different from timbre performance ( $M = 2.7$ ,  $SD = 1.2$ ),  $t(79) = 2.62$ ,  $p = .055$ , but pitch performance was significantly better than timbre performance  $t(79) = 3.21$ ,  $p = .009$ ,  $d = 0.36$ , 95% CI [0.0, 0.8]. This pattern of results was mainly due to greater salience between distractors and targets for timbres at level 1 than at level 2. Indeed, whereas the vibes timbre (distractor) was highly distinct from the flute timbre (target) at level 1, the cello timbre (distractor) was often mistaken for the flute timbre at level 2, which led to a higher rate of false alarms and a decrease in performance.

#### Supplementary Material S5.2

##### *Details of the Post-hoc Analyses for the Main Effect of Group*

Regarding the main effect of group, post-hoc comparisons using Bonferroni correction indicated that DYS+A children ( $M = 2.9$ ,  $SD = 1.3$ ) performed significantly worse than both DYS-A children ( $M = 3.7$ ,  $SD = 1.2$ ),  $t(28) = -2.85$ ,  $p = .034$ ,  $d = -0.32$ , 95% CI [-1.6, 0.0], and CA controls ( $M = 4.1$ ,  $SD = 1.1$ ),  $t(38) = -4.74$ ,  $p < .001$ ,  $d = -0.53$ , 95% CI [-1.87, -0.51], but

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not significantly different from RL controls ( $M = 3.0$ ,  $SD = 1.3$ ),  $t < 1$ , the latter also performing significantly worse than both DYS-A children,  $t(48) = -2.82$ ,  $p = .037$ ,  $d = -0.32$ , 95% CI [-1.4, 0.0], and CA controls,  $t(48) = -5.05$ ,  $p < .001$ ,  $d = -0.56$ , 95% CI [-1.7, -0.5]. No other group difference was significant (all  $ps > .745$ ).

**Supplementary Material S6**

**Correlation Analysis**

**Table S6.1**

*Partial Correlations Between MIM Index, MBEMA Score, and Performance for Each Composite Variable as a Function of Group*

(a) All

Task	Composite variable	df	r	
			MIM index	MBEMA score
Auditory short-term memory	Word	72	<b>.37*</b>	<b>.37*</b>
	Pitch	72	<b>.36*</b>	<b>.58***</b>
	Item	72	<b>.35*</b>	<b>.52***</b>
	Order length 3	72	.24	<b>.54***</b>
	Order length 4	72	<b>.40*</b>	<b>.44**</b>
Auditory perceptual awareness	Syllable	72	.26	.33
	Phoneme	72	.33	.24
	Interval	72	.30	<b>.56***</b>
	Note	72	.24	<b>.39*</b>
	Timbre	72	.18	<b>.40**</b>
Auditory attention	Global	72	<b>.37*</b>	<b>.44**</b>

(b) DYS+A

Task	Composite variable	df	r	
			MIM index	MBEMA score
Auditory short-term memory	Word	9	-.13	.29
	Pitch	9	.18	-.49
	Item	9	-.30	.11
	Order length 3	9	.25	.01
	Order length 4	9	.04	-.35
Auditory perceptual awareness	Syllable	9	.08	.02
	Phoneme	9	.13	-.08
	Interval	9	-.08	.01
	Note	9	-.31	.31
	Timbre	9	.21	.37
Auditory attention	Global	9	-.32	.24

(c) DYS-A

Task	Composite variable	df	r	
			MIM index	MBEMA score
Auditory short-term memory	Word	9	.05	.57
	Pitch	9	.17	.57
	Item	9	.24	.65
	Order length 3	9	.54	.28
	Order length 4	9	-.27	.59
	Syllable	9	.11	.13

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Auditory perceptual awareness	Phoneme	9	.27	.09
	Interval	9	.34	.57
	Note	9	.42	.43
	Timbre	9	.24	.21
Auditory attention	Global	9	.43	-.19

### (d) CA

Task	Composite variable	df	r	
			MIM index	MBEMA score
Auditory short-term memory	Word	19	.18	.20
	Pitch	19	.31	.49
	Item	19	.32	.41
	Order length 3	19	.04	.43
	Order length 4	19	.31	.31
Auditory perceptual awareness	Syllable	19	-.34	-.03
	Phoneme	19	-.04	.32
	Interval	19	.29	.45
	Note	19	.01	.42
	Timbre	19	.06	.07
Auditory attention	Global	19	.04	.13

### (e) RL

Task	Composite variable	df	r	
			MIM index	MBEMA score
Auditory short-term memory	Word	17	.40	.07
	Pitch	17	.15	.30
	Item	17	.12	.19
	Order length 3	17	.09	.22
	Order length 4	17	<b>.67*</b>	.14
Auditory perceptual awareness	Syllable	17	-.02	-.18
	Phoneme	17	.43	.05
	Interval	17	-.42	.43
	Note	17	-.05	.14
	Timbre	17	.02	-.05
Auditory attention	Global	17	.14	.22

*Note.* Correlations are shown (a) across groups, (b) within the group of DYS+A children, (c) within the group of DYS-A children, (d) within the CA control group, and (e) within the RL control group after partialing out age, parents' SES, music education, and nonverbal intelligence. DYS+A: dyslexic children with amusia, DYS-A: dyslexic children without amusia, CA: chronological-age matched controls, RL: reading-level matched controls. *P*-values

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are reported after being Bonferroni-corrected for multiple comparisons. In bold: significant correlations.

<sup>a</sup> The performance of the two RL controls who probably did not understand some of the tasks is not included in the analysis.

\*  $p < .05$ . \*\*  $p < .01$ . \*\*\*  $p < .001$ .