The neural localization of musical score reading

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Laymen summary

An overview is provided on the brain areas involved in musical score reading. The reading of musical scores is a complex process in which brain areas in different parts of the brain are active. These areas are predominantly located in the left brain half. They are involved in general processes like memory and action performance and are probably part of a score-reading network that expands over the different neural regions. The areas are not completely overlapping with brain areas involved in language reading. Possibly the music- and language reading sites are distinct but adjacent. This information provides a helpful background in defining the essential brain areas of an epileptic violinist in the preparation for a planned surgery.

Abstract

This literature review addresses the neural regions that are involved in musical score reading and the possible overlap with language reading, in order to provide a decent overview on the scarce literature on music reading research. The reading of musical scores is a complex process in which brain areas in the parietal, occipito-temporal and frontal lobes are involved. Especially areas in the dominant parietal lobe, the fusiform gyrus and the frontal gyri are active during score-reading. These areas also regulate general cognitive processes like memory- and motor actions, including sensory-motor integration, and are probably part of a score-reading network that expands over the different neural regions, predominantly lateralized to the left hemisphere. The neural sites that are active in language reading are spatially separated from the areas involved in music reading, though they are adjacent. In order to preserve score reading related areas in epileptic surgery, presurgical electrocortical stimulation should also include a score reading task, defining the music-related areas in the dominant parietal, occipito-temporal and frontal lobes.

Introduction

The ability to read a musical score is for classical musicians almost as essential in their daily life as the ability to read verbal language. The sight reading of musical scores is a highly complex cognitive performance. It requires at the very least interpretation of the pitch and duration of the notes in the light of the key signature and meter, the detection of patterns and intonation of the notes in anticipation on what the music should sound like (Peretz & Zatorre, 2005). When all these aspects are processed, the information subsequently has to be translated into a suited motor plan in order to perform the music on a specific instrument. Despite a large body of literature on the neuroscience of language reading, the neuroscience of musical score reading is a less developed study field that has not received the attention paid to other areas of music research. Many musicological studies focus on other aspects of music like the neural effects of listening to music. Nevertheless, although they are scarce, in the past few years there are some studies performed on neural lateralization and localization of music reading. In this thesis an overview on this research is provided.

Also studies on the possible neural overlap between language- and music reading will be reviewed, as reading musical scores shows obvious similarities with the reading of language. In both kinds of reading, coded information has to be transformed into an understandable representation in the brain. They both are rule-based systems composed of basic elements like notes, chords, phonemes and words. These elements are in turn combined into higher-order elements like musical themes and sentences by the rules of harmony or syntax (Besson & Schön, 2001). However, differences between language and music are present too. Whereas text reading occurs horizontally, music reading involves decoding a vertical dimension (pitch) over time. Moreover, music reading involves the decoding of both single elements (notes) and elements in combination (chords). Another difference is that musical script holds information about duration of the notes, whereas in language no information on pace is given. Besides, in language reading the meaning of a sentence is not critically changed when the pace of a sentence is changed. (Sloboda, 1980)

The question whether language and music have shared origins or not exists for already a long time. From the seventeenth century on, philosophers and scientists are in debate about the roots of the two systems. Darwin for example addressed the topic in his 'The descent of man' (Darwin, 1871). He argued that music and language have a common origin, however language evolved first and music evolved out of the reproductive calls of primates. It seems to be an object of consensus in literature that the core function of language and music was to express emotive meaning through variations in rhythm and the intonation of the voice (Besson & Schön, 2001). This literature review aims to provide more insight in the recent studies on this debated topic.

Overall, this thesis states as a central question 'What are the neural substrates of musical score reading and how do they relate to the neural regions of language processing?'. The review is of practical use in a current case in the UMC Utrecht where in a few months an epileptic violinist will be under surgery for the implantation of subdural electrodes in the left temporo-parieto-occipital area. These electrodes are implanted to determine the exact beginning of an epileptic seizure. Before surgery the neural location of essential functions will be defined using electrocortical stimulation. Since the patient is a musician and reading musical scores is therefore a very important function for him, electrocortical stimulation will also be applied in areas involved in musical score reading. The outcomes of this literature review will hopefully be useful in preparing the surgery of the epileptic violinist.

Methods

The literature reviewed is searched in the online databases Pubmed, Scopus and Google Scholar. As preferred document type, articles and reviews were selected. No limitation for the age of publications was given. The search terms used were 'music reading', 'music reading localization', 'music reading lateralization', 'music and language reading' and several variations on these terms, adding or removing the words ‘neural’ or ‘brain’ to the search terms. ‘Music’ is in all search terms also substituted by ‘score’ or ‘musical score’. From the search output the neurobiological articles and reviews were selected that addressed musical score reading. All kinds of studies were selected; both neuroimaging studies, direct stimulation studies, EEG-studies, lesion studies and single case studies were included in the reference list.

Besides this search in online databases the snowball search method is used. Via the databases several key references were found. Subsequently, the reference lists of these key references gave access to a second pool of potentially useful articles. The articles from these reference lists were also scanned for their value in this review. In total, forty studies are included in this review.

Results

Lateralization

Many cognitive actions are predominantly processed by one of the two brain hemispheres. The reading of language for example, is in the majority of healthy right-handed participants found to be mainly processed in the left hemisphere (Knecht *et al.*, 2000). Looking at neural activation of musical score reading raises the question if music reading is also lateralized in the brain.

Indeed, musical score reading seems to be lateralized too. Neuroimaging studies - that will be discussed in the paragraph on localization - point in the direction of a left-sided lateralization for music reading. Several fMRI and PET-scan studies showed an activation of the left parietal lobe during music reading in musicians (Sergent *et al.*, 1992, Stewart *et al.*, 2005, Meister *et al.*, 2004, Roux *et al.*, 2007). Mainly the supramarginal gyrus and the intraparietal sulcus were activated. The left hemisphere is particularly involved in music syntactic processing, such as free recall of notes when a musician reads a score. In a study that focused on the lateralization of music reading, a young professional musician suffering from refractory left medial temporal lobe epilepsy could read a presented score perfectly when her right hemisphere was anesthetized (Trujillo-Pozo *et al.*, 2013). However when her left hemisphere was anesthetized, she could not free recall the notes anymore, again indicating the major role of the left hemisphere in score reading. Yet this study also revealed a role of the right hemisphere. The right lobes seems to be important in remembering of previously seen musical scores. When the patient was asked to look at scores and choose

Authors	Text reading	Music reading			Lesion site
		Pitch reading	Rhythm reading	Symbol reading	
Levin & Rose (1979)	-	- ?	+ ?	+/-	Left splenio-occipital and left occipital pole
Brust (1980) Case #1	-	-	+	+	Left inferior temporal and temporo-parietal lobe, and left anterior temporal lobectomy
Brust (1980) Case #2	-	-	-	-	Left posterior temporal and inferior parietal lobes
Mavlov (1980)	+ Recovered	+ ?	-	+ ?	Left posterior parietal lobe
Judd, Gardner & Geschwind (1983)	-	-	+	+/-	Left occipito-temporal lobe
Basso & Capitani (1985)	-	+ Naming -	+	+	Left temporo-parieto-occipital lobe + posterior part of the right temporal lobe
Fasanaro, Spitaleri, Valiani & Grossi (1990)	-	-	+	+	Left temporoparieto-occipital lobe and thalamus
Stanzione, Grossi & Roberto (1990)	+/-	+/- ?	+/- ?	+	Left posterior temporo-parietal lobe
Hofman, Klein & Arlazoroff (1993)	-	-	-	-	Postero-lateral border of the left ventricle and hypodense left parieto-occipital area
Horikoshi, Asari, Watanabe et al. (1997)	-	-	+	N/A	Left occipital lobe and posterior part of tem-poro-parietal lobe
Beversdorf & Heilman (1998)	+/-	N/A	N/A	N/A	Bilateral posterior cortical, most prominent on the left side
Cappelletti et al. (2000)	+	-	-	+	Left posterior temporal lobe and small right occipito-temporal
Kawamura, Midorikawa & Kezuka (2000)	+ Recovered	+/- Recovered?	+	+	Left angular gyrus
Midorikawa & Kawamura (2000)[1]	+	+	-	+	Left upper parietal lobule
Schön, Semenza & Denes (2001)	+/-	+Naming - (*F clef only*)	-	+/-	Left temporo-parietal lobe
Midorikawa, Kawamura & Kezuka (2003)	-	+	-	+/-	From Left superior temporal gyrus to angular gyrus

Legend :

+	no deficit	N/A	information not available
-	deficit	?	unclear from the text
+/-	light deficit or incomplete information		

Fig. 1. Overview on single-case studies in patients with music reading problems. This review reveals that all patients suffer from damage in the left hemisphere, indicating the importance of the left hemisphere in the processing of musical scores (Hébert & Cuddy, 2006).

which score she had seen before in a previous condition of the study, she could not perform it correctly when her right hemisphere was anesthetized. When only her left hemisphere was anesthetized, she could remember the scores perfectly. Probably this is because of the role of the right occipito-temporal lobe in score recognition, as discussed earlier (DeHaene & Cohen, 2011).

More evidence for a left-sided lateralization in music reading comes from single-case studies. A review on several different studies on patients with music reading problems revealed that all of these patients suffered from neural damage in their left hemisphere (Fig. 1, Hébert & Cuddy, 2006). Although the exact lesion sites vary, all damage sites are located in their left hemisphere. It is therefore evident from this table that music reading relies heavily on the left hemisphere. Combined with the imaging studies discussed above, it is reasonable to assume that music reading seems to be lateralized predominantly in the left lobes of the brain.

Localization

Parietal lobe

<u>Supramarginal gyrus</u>

One of the first studies addressing the neural basis of musical score reading is a study using Positron Emission Tomography (PET-) scans (Sergent *et al*., 1992). The PET-experiment consisted of different music-related tasks like sight-reading, listening and playing on a keyboard while the brain activity of the participants was measured. The participants were professional pianists. This early study demonstrated brain activation during score reading in several regions, under which the posterior part of the left supramarginal gyrus (Fig. 2). The PET-study of Sergent and colleagues is seen as the basis of neural research on musical score reading and will also be discussed in paragraphs concerning other brain regions. However, years after publication of the study it received critique on the control stimuli (Schön *et al.*, 2002). The visual dots that were used did not visually match the musical score. Therefore no

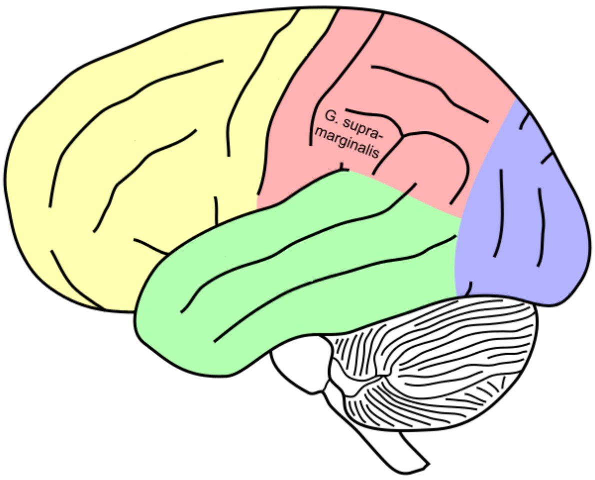


Fig. 2. Location of the supramarginal gyrus in the parietal lobe (Adapted from reference 39).

claims on the specificity of the visual areas for music sight-reading can be made with this paper as a basis.

However, in a much later study electrocortical stimulation was used to map brain areas involved in musical score reading, language reading and Arabic number reading (Roux *et al.*, 2007). Unless direct stimulation is a useful tool in deciphering the brain regions involved in music reading, many cortical areas remain inaccessible to direct stimulation. This is a limitation that certainly has to be taken into account when analyzing data from direct stimulation studies (Roux *et al.*, 2007). In the results of the direct stimulation study, the role of the supramarginal gyrus was emphasized again. The research group combined the data of seven musical patients that underwent surgery for brain tumors or vascular lesions between 1996 and 2005. In order to locate essential regions prior to these surgeries, the patients performed reading tasks while they received electrocortical stimulation on different brain areas. In case the patients made a reading mistake following stimulation of a specific area, this area was assumed to be essential to perform the task correctly. For score reading, three types of errors were detected, evoked by stimulation of specific brainareas (Fig. 3). Two of these error-types, the score reading hesitation and the score reading paraphasia are described below. The third type of error, the score-reading arrest, is addressed in the paragraph on the frontal lobe.

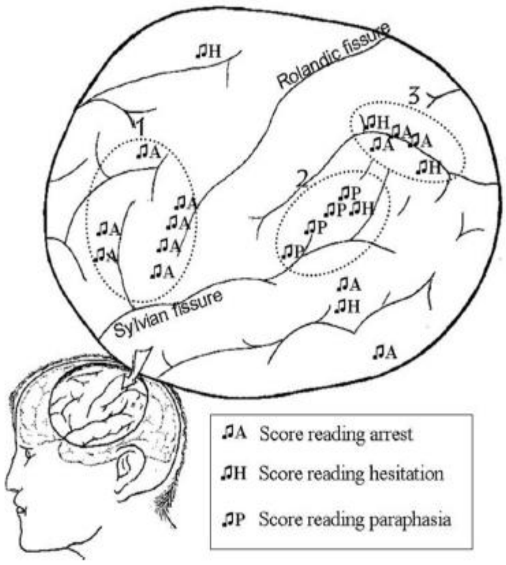
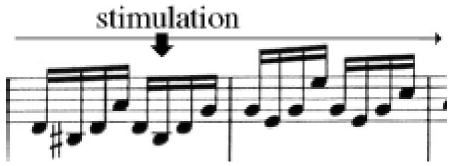


Fig. 3. Types of errors after electrocortical stimulation of involved brain areas (Roux *et al.*, 2007)

1. Score reading hesitation

Upper part supramarginal gyrus, regions close to intraparietal sulcus

Stimulation of these areas lead to abrupt errors and hesitations in the reading of the score, while the patient was able to read the score perfectly before stimulation. For instance, the score below was read as follows:



"D, B, D, A, D, B, D ... G ... is that right?... G again.... D? no ... C? no ... E ... that's E, …" (The correct notes are D, B, D, A, D, B, D, G, G, E, …).

2. Score reading paraphasia

Supramarginal gyrus

After stimulation of the anterior and lower part of the left supramarginal gyrus, score reading was fluent yet incorrect. This is similar to paraphasia phenomena for words. For instance, the score below was read as follows:

"G, C, G, C, F, D, F, D, G, F, D, D, F, A, E, A, C, F, B, B, ..."
(The correct notes are G, C, G, C, F, D, F, C, G, E, G, C, G, E, G, B, G, E, G, A, …)

Taken the data together, the Roux-study particularly highlights the role of the supramarginal gyrus in score reading again. Also functional Magnetic Resonance Imaging studies found a role of the supramarginal gyrus in reading musical scores (Steward *et al.*, 2003, Steward, 2005). These studies focused on trained musical score reading instead of sight-reading. In both studies non-musically trained participants received musical training for almost three months. Before training, the brain of the participants did not distinguish between musical notation and nonmusical notation. However, after training the supramarginal gyrus became active when the participant was presented with musical notation stimuli (Steward, 2005).

Still the supramarginal gyrus seems not specifically involved in the reading of the notes itself. Neuroimaging studies, transcranial magnetic stimulation (TMS) studies and patient studies highlighted the involvement of the area in the processing of motor intention (Rushworth *et al.*, 2001a&b). In other words: the activation of the supramarginal gyrus found during score reading is possibly caused by the fact that musicians learn to make an association between the notes on the score and a specific fingering on their instrument. The visual appearance of the notes are unconsciously interpreted as an instruction to act (Steward *et al.*, 2003). Moreover, the supramarginal gyrus becomes active in the reading of words and numbers too (Schon *et al.*, 2002), indicating that it is probably not an music reading-specific area.

Superior parietal cortex

Another region that is found to be involved in the reading of musical scores is the parietal cortex, in particular the superior parietal cortex (Fig. 4). The early PET-scan study of Sergent and collegues already found an association of the area with score reading (Sergent *et al.*, 1992). When the participants performed a task in which they had to sight-read music, play and listen simultaneously, the superior parietal cortex was activated. However, this region was not activated when the participants only read music or only listened to music. These findings were confirmed by later fMRI-studies (e.g. Schon *et al.*, 2002). Pianists were placed in an fMRI-scanner while reading and playing notes on a little keyboard. The neural activation during this task was compared with the neural activation while the musicians read numbers or verbal language. The superior parietal cortex showed activity during music reading specifically. This activity is possibly due to the movement and muscle tension of the hands of the pianists in the scanner, or to sensory-motor integration. However, the earlier mentioned study of Steward, working with musically naïve participants who received musical training before the study, also found evidence for involvement of the superior parietal cortex in score reading (Stewart, 2005). In the fMRI-scanning session after training the participants named notes based on their newly acquired musical literacy skills. Activation was seen in the superior parietal cortex. The area showed learning-related changes especially for melody reading.

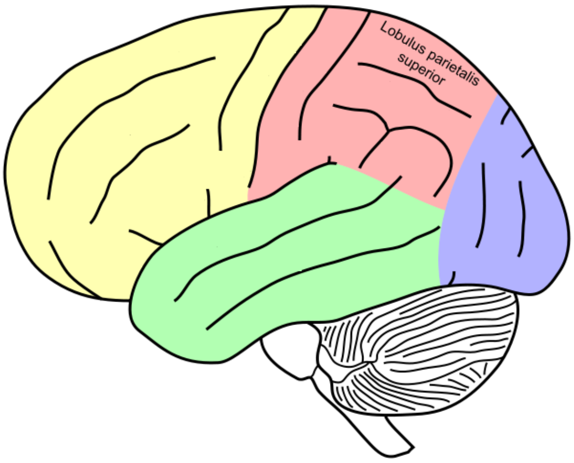


Fig. 4. Location of the superior parietal cortex in the parietal lobe. (Adapted from reference 39).

A study in which the grey matter volume in professional musicians, amateur musicians an non-musicians was measured revealed that this grey matter volume in the superior parietal region showed a positive correlation (Gaser & Schlaug, 2003). This means that it was highest in the group of professional musicians, intermediate in the group of amateur musicians and lowest in the group on non-musicians.

The level of activation in the superior parietal cortex in reaction of music reading is independent of the level of musical experience. Experienced musicians did not have a larger activation of the superior parietal areas than novices (Stewart, 2005). This assumption is supported by Roux and colleagues, who found that highly trained musicians did not have more or more specific score-reading sites than novice musicians (Roux *et al.*, 2007).

Finally, the parietal cortex probably has a role in the processing of the visuo-spatial element of music reading (Steward, 2005, Roux *et al.*, 2007). Note- and score reading both require extensive visuo-spatial analysis. Scores are read by analysis of the positions of the notes on a staff, in order to determine the pitch of a certain note. As the parietal areas are part of the neural dorsal visual route that processes visuo-spatial information in general, it is plausible that these areas also fulfil a visuo-spatial role in the processing of musical information.

<u>Intraparietal sulcus</u>

Functional Magnetic Resonance Imaging and Positron Emission Tomography scanning revealed that the intraparietal sulcus (IPS) is activated during score reading in musicians. The IPS is the sulcus between the superior and inferior parietal lobe (Fig. 5). The early PET-scan study of Sergent and colleagues already indicated the involvement of the IPS in score reading (Sergent *et al.*, 1992). And also for this region the following fMRI-studies in the field found supporting evidence for the involvement of the intraparietal sulcus (Schon *et al.*, 2002, Meister *et al.*, 2004, Stewart, 2005). The intraparietal sulcus is one of the two music reading specific areas of the brain found by Schon and colleagues (Schon *et al.*, 2002). Like the superior parietal cortex, the IPS showed activation in response to music reading rather than to language and number reading. Moreover, the IPS is in particular involved in the processing of rhythmical components of

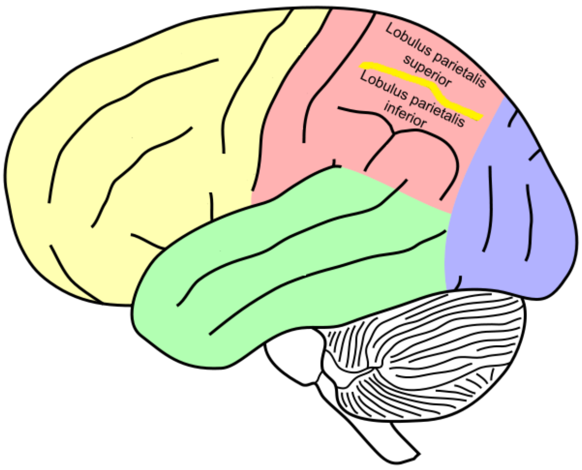


Fig. 5. Location of the intraparietal sulcus in the parietal lobe. The intraparietal sulcus is indicated by the yellow line (Adapted from reference 39).

music (Meister *et al.*, 2004). The essential role of the IPS in rhythm monitoring was earlier found in a non-musical study on time perception in different modalities (Schubotz *et al.*, 2000). Finally, also the direct stimulation study of Roux and colleagues found involvement of regions close to the intraparietal sulcus (Roux *et al.*, 2007). Patients were not able to read musical scores anymore when the regions close to the sulcus were electrically stimulated, indicating an essential role for the regions in score reading.

The IPS is part of the superior parietal lobe that mainly processes sensorimotor integration (Jancke *et al.*, 2001). The area is also involved in eye–hand coördination. An fMRI study aimed to map the activity of parietal areas during different cognitive tasks found the involvement of the IPS in visuospatial processing (Simon *et al.*, 2002). This is probably the reason for the activity of the IPS during musical score reading: eye-hand coordination is essential for the translation of notes to the movement of the fingers on the musical instrument. Also a combined lesion/fMRI study revealed that the IPS is involved in sensorimotor integration of precisely tuned finger movements in humans. Lesions in the IPS lead to difficulties in finger movements (Binkofski *et al.*, 1998).

Temporal and occipital lobe

Evidence for the involvement of temporal and occipital lobes in music reading is found in several neuroimaging studies (Nakada *et al.*, 1998, Parsons, 2001, Schon *et al.*, 2002, Roux *et al.*, 2007). In these lobes, the occipito-temporal gyrus is mainly active in the processing of musical scores. This site is often called the fusiform gyrus and is located between the inferior temporal lobe and the parahippocampal gyrus (Fig. 6). Learning related changes in this area

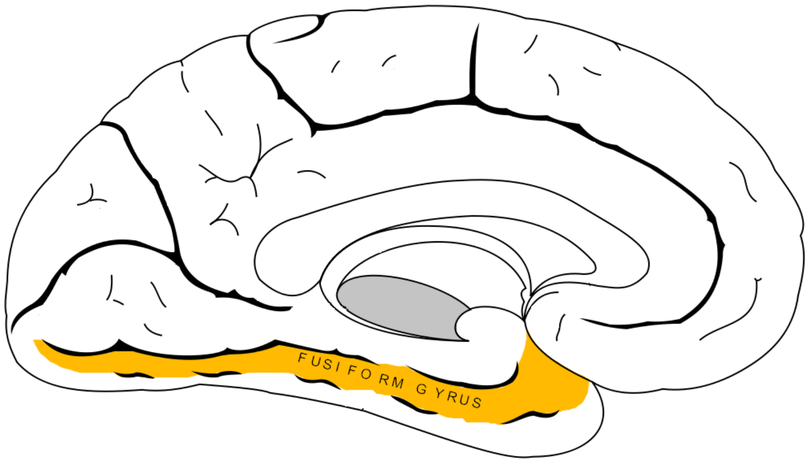


Fig. 6. Location of the fusiform gyrus in the occipital/temporal lobe. This gyrus is located deeper in the brain than the other areas. (Adapted from reference 40).

are documented for music reading, in particular rhythm reading (Steward, 2005). Furthermore an EEG-study found evidence for the involvement of the fusiform gyrus in score reading (Proverbio *et al.*, 2013). The ability to read letters forming a word and notes forming a measure was compared in musicians and musically naïve controls, while event related potentials (ERPs) were measured. The overall brain response to musical notes was much larger in musicians than in controls. This is not a surprising insight as notes have less meaning to controls compared with the musicians. Subsequently LORETA source reconstruction was performed. This is a technique to spatially locate the electric activation recorded by EEG electrodes. LORETA analysis revealed an involvement of both the left fusiform gyrus and the right fusiform gyrus in note recognition in musicians. The activation of the right fusiform gyrus could be the analogue of a language area in the left hemisphere; the visual word form area in the left occipito-temporal lobe (Parsons, 2001, Schon *et al.*, 2002). When lesions occur in this area, this can cause problems with the recognition of words (DeHaene & Cohen, 2011).

Frontal lobe

In the frontal areas of the brain the superior, middle and inferior frontal gyri are indicated as score reading areas (Roux *et al.*, 2007)(Fig. 7). Of these three gyri, only the left superior frontal gyrus solely responded to score-reading in the study, i.e. it was score-reading specific and was not active during word- or number reading. This region is located at the upper part of the frontal lobe and is also involved in working memory processes (Du Boisqueheneuc *et al.*, 2006). Next to the left superior frontal gyrus, also the middle and inferior frontal gyri showed an involvement in the sight reading of scores. The middle frontal gyrus is also active in working memory processes (Goldman-Rakic, 1996, Proverbio *et al.*, 2013). Music reading is a skill that needs a large working memory capacity (Bergman Nutley *et al.*, 2013). However, in much more processes like language or number reading working memory has an essential role. Indeed the middle frontal gyrus became active during language- and number reading tasks (Roux *et al.*, 2007). Therefore the middle frontal gyrus is not seen as a music reading specific area.

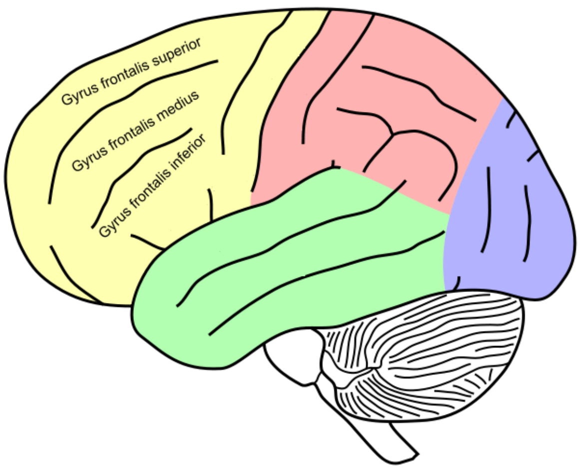
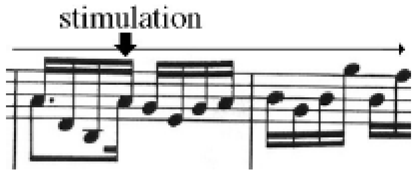


Fig. 7. Location of the superior, middle and inforerior frontal gyri in the frontal lobe. (Adapted from reference 39).

Stimulation of the inferior frontal gyrus and the precentral gyri lead to an abrupt stop in music reading (Roux *et al.*, 2007). During electrocortical stimulation patients started reading the score below correctly as: “A, D, B, A, G....”. Yet as soon as stimulation on the inferior frontal gyrus and precentral gyri was applied, the patient abruptly stopped reading.



This is however a far from surprising result, as both areas are involved in motor action and the articulatory pathways in particular. Also Broca’s area, involved in speech, is for a small extend located on the inferior frontal gyrus. The patients therefore probably stopped talking because of interference in the articulatory pathway instead of interference in musical score reading.

Score-reading network

Taking the studies on the neural basis of musical score reading together, it is clear that the neural activation is wide-spread over the cortex. Roux and colleagues designed a helpful figure on the localization of score reading activity, including six of the most recent studies at that time in order to summarize the most activated sites (Roux *et al.*, 2007) (Fig. 8). The left and right hemispheric regions involved in music reading are depicted by circled notes. Most possible these regions do not work independently in the processing of score reading. They are more probably part of a larger score reading network, in which the areas each perform a specific stage of processing. This network processes the enormous amount of simultaneous and sequential information in a very brief time that have to be processed in music reading (Peretz & Zatorre, 2005). Sergent and colleagues claimed already in 1992 that there is “no musical reading center, but a network of structures participating in score reading” (Sergent *et al.*, 1992). Sergent stated that sight-reading is processed by a cerebral network that is spread over the four cortical lobes and the cerebellum. Looking at the findings depicted in figure 8, derived with more modern research methods, we see that he was probably right about the locations (Fig. 8). Moreover, also recent research (e.g. Meister *et al.*, 2004, Roux *et al.*, 2007) agrees on the idea of a music reading network in the brain. The suggested pathway is indicated by the white arrows (Roux *et al.*, 2007). The first stage of note analysis could be the activation of the right fusiform gyrus. From there, the score could subsequently be processed in the left occipitoparietal areas and the frontal areas.

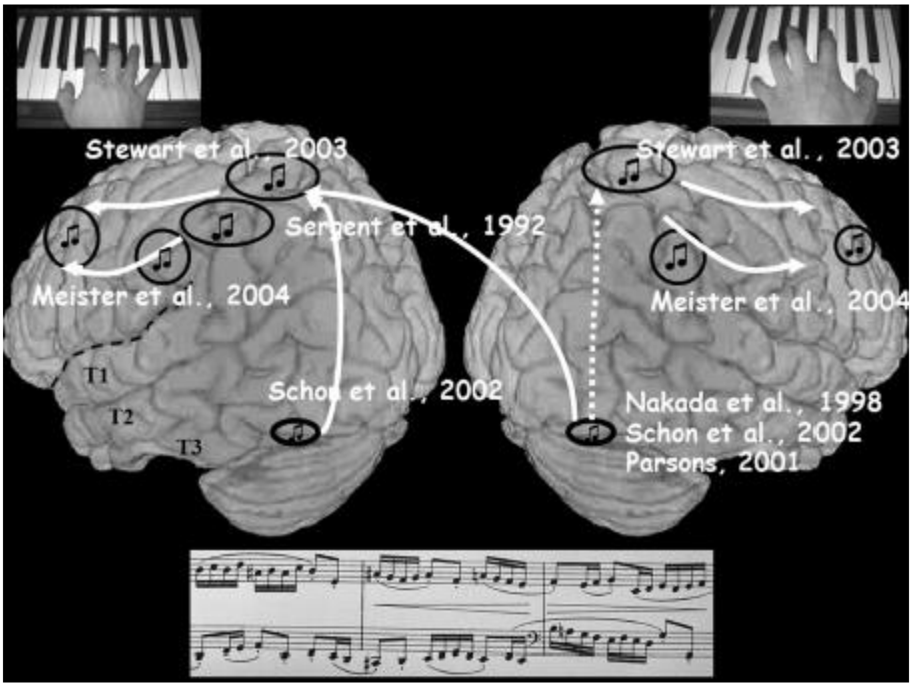


Fig. 8. Findings of a selection of recent neuroimaging studies on the neural localization of musical score reading. Circled musical notes indicate regions activated during music reading. The white arrows give a suggested neural pathway in music reading processing (Roux *et al.*, 2007).

Overlap with language

Single case studies

Several studies report cases of individuals with brain lesions that have an influence on the ability to read musical scores, texts, or both. These studies are mostly single case studies presenting data of patients with lesions in different brain areas, and corresponding disabilities. The cases can be structured in three categories: patients who suffered from both verbal alexia (disabled word reading) and music alexia (disabled music reading), patients who suffered from music alexia but not from verbal alexia, and patients who suffered from verbal alexia but not from music alexia. The amount of conflicting single case studies has led to confusion about the brain regions involved in reading texts and/or musical scores. A selection of the single case studies are highlighted below.

- *Music alexia without verbal alexia*

Patient PKC was a professional musician that suffered from music alexia without verbal alexia, due to an episode of haemorrhagic encephalitis (Cappelletti *et al.*, 2000). A herpes simplex virus damaged her left postero-lateral temporal cortex and her right occipitotemporal junction. This led to severe disruption of her musical reading skills, but left her language reading ability intact. She was unable to read musical notes in all possible ways (naming, singing, playing, matching with written note names). However, when PKC was tested on musical symbols other than notes (such as dynamic or tempo-related signs) or reading aloud numbers, letters, words and sentences, she performed flawlessly or at a very high level. This implicates that the affected areas were specific for music reading.

- *Verbal alexia without music alexia*

The contrary of the case described above is documented for a musician who suffered from a left occipital lobe infarct that affected his reading abilities but not his musical skills (Judd *et al.*, 1983). He was alexic for both words, letters and numbers, but continued to read music very well and continued to compose and conduct orchestras. This verbal alexia with sustained musical abilities is also discovered in the blind. A single case study reported about a 77 year old blind man with an infarct in the territory of the left middle cerebral artery; the temporal and inferior parietal lobes (Signoret *et al.*, 1987). After his infarct the man was no longer able to read and write in braille. However, he kept played the organ very well and even composed pieces of music for the organ in braille. In other words: he could still read the braille symbols for music, but not for language. Also musical abilities like harmony and rhythm were preserved, and he could still read and sing musical notes and could copy them. This early example gives a striking indication for the at least in part neural independence of linguistic and musical competences.

- *Combined music alexia and verbal alexia*

However, the verbal and musical deficiencies caused by brain damage can also occur simultaneously. A famous example of this combined music alexia and verbal alexia is the French composer Maurice Ravel. He suffered from a still unknown progressive cerebral disease that slowly affected his ability to compose (Amaducci *et al.*, 2002). Other cases in which brain damage selectively impairs music reading and/or writing and not the reading of other symbols include the studies of Brust (Brust, 1980). He found impaired language and music reading function in two professional musicians who suffered left hemispheric lesions.

Yet another single case study that illuminates the case of a patient suffering from music alexia and verbal alexia, is the study of Stanzione and collegues (Stanzione et al. 1990). Here a young musician was studied that suffered from a head injury leading to damage in the left temporoparietal areas, the parietal and posterior parietal regions. This damage led to difficulty in both reading music and reading words. The patient was able to read notes, yet very slowly, as when she began to learn music. The authors suggested that music and word reading could have at least in part the same neural architecture. Also data from early research on an older musician with lesions in the left temporoparieto-occipital region provided equivalent results: his word and music reading abilities were both impaired (Fasanaro *et al.*, 1990). His text reading showed pure verbal alexia, in which both word-processing routes were damaged. Note reading results were analogous to the results of word reading. However, in score reading he was still able to read rhythmical information and ideograms.

Neuroimaging studies

Although meta-analyses exist for the processing of language, neuroimaging studies on the comparison of music and language reading are very scarce. One of the reasons for this difficulty is the theoretical problem of deciding which level of language processing is best compared with which level of processing in music (Besson & Schön, 2001). The body of literature on the comparison of brain areas that process music and language reading specifically is even smaller. The main experiment in the comparison between music- and language related areas is the study of Roux and colleagues (Roux *et al.*, 2007). Using direct cortical stimulation, they indicated that regions that are involved in score reading are usually distinct from the areas that are involved in language reading. Overall, in most subjects the intraparietal sulcus and the middle temporal gyrus were music reading specific, i.e. were found to be involved in music reading but not in language- or Arabic number reading. For language reading, only specific parts of the supramarginal gyri were language reading specific. These findings of a distinct neural basis of music- and language reading confirm the ideas derived from single case studies described above. Still Roux and colleagues also found areas that were involved in the processing of both score reading and language reading. These were other parts of the supramarginal gyrus, the frontal gyri and the posterior part of the superior temporal gyrus (Roux *et al.*, 2007). However, not all subjects showed this activation; the activation patterns differed strongly between patients.

Discussion

Lateralization and localization

The studies described above indicate that several different brain areas seem to play a role in the processing of music reading. For almost all of these areas the involvement in music reading can be easily explained by their function as found before in more general research. In the parietal lobe, the supramarginal gyrus is related to motor actions. The intraparietal sulcus is involved with eye-hand coordination. Then, in the occipito-temporal lobe, the fusiform gyrus becomes active in recognition. In the frontal areas, the middle frontal gyrus and the left superior frontal gyrus is a working-memory area, and the inferior frontal gyrus is a motor area again. All these motor-, coordination-, memory- and recognition functions are obviously needed in reading a score and transferring the notes into a movement of the fingers on the instrument. Yet these areas are involved in such general principles that they are also involved during other cognitive tasks and are therefore not purely score reading specific.

Furthermore, a recent study argues that general cognitive skills such as memory capacity do not play a significant role in sight-reading (Kopiez & Lee, 2008). In this model the ability to read music is seen as a combination of practice-related variables and genetically determined variables: the age a musician started to read music, psycho-motor speed, mental speed and the ability for auditory imagery. The combination of brain capacity with early experience and practice therefore may be the key to proficiency in music reading.

Overlap with language

Hébert and Cuddy have summarized the single case studies on music reading impaired persons from the recent past years in a useful table (Fig. 1) (Hébert & Cuddy, 2006). This table indicates whether a patient was able to read text, pitch, rhythm and musical symbols. Also the affected brain sites are given. Note that only the cases in which music reading was impaired in some way are included in the schema. Studies that are here categorized in the 'verbal alexia without music alexia' group are therefore not discussed. Hébert and Cuddy showed that in these at least in part musically affected persons, very few out of the sixteen patients had a dissociation between language and music reading, i.e. could read language but were impaired in reading scores. This is for example the case of patient PKC that we enlightened earlier (Cappelletti *et al*., 2000). The rest of the patients that were partially impaired in music reading also showed difficulties in reading. An explanation for this high rate of cases that show a combined music alexia and verbal alexia is that the neural substrates of language and music are probably distinct but adjacent. Hence a lesion can easily damage an area that contains crucial sites for the processing of both music and language reading (Amaducci *et al.*, 2002, Hébert & Cuddly, 2006). Text and music reading is therefore functional autonomous, but is not as independent as it may look due to the structural neural proximity (Hébert & Cuddly, 2006).

Also the neuroimaging studies discussed show that music- and language reading are probably not processed by regions that are located at exactly the same neural site. A neuroimaging study that compared brain activity during the two forms of reading found the intraparietal sulcus and the middle temporal gyrus as score reading specific areas, i.e. not language reading areas. Unfortunately very little research has been performed on the direct comparison between music- and language reading. Especially neuroimaging literature on this topic is scarce.

Finally, a suggested interesting experiment on language and music reading could be the direct stimulation of Broca's area, involved in speech production. This area is located on the middle and inferior frontal gyrus, regions that are also found to be involved in musical score reading (Roux *et al.*, 2007). In language tests a speech arrest occurs when Broca's area is stimulated during text reading. It could be interesting to test whether this speech arrest also occurs when musical notes are read or sung during stimulation of Broca's area. No study was found in which this experiment is done; only a study is present on the speech-arrest evoking stimulation of the inferior frontal gyrus as a whole (Roux *et al*., 2007).

Conclusion

This thesis aimed to provide an answer to the question 'What are the neural substrates of musical score reading and how do they relate to the neural regions of language processing?'. After reviewing several studies of different types and ages, the answer to the question can be stated as follows.

Literature on neural lateralization and localization of music reading is reviewed, leading to the conclusion that many regions are involved in the processing of a musical score. In the parietal lobe these are the supramarginal gyrus, the superior parietal cortex and the intraparietal sulcus. In the occipito-temporal lobe this is the fusiform gyrus and in the frontal areas the middle frontal gyrus, the left superior frontal gyrus and the inferior frontal gyrus. These areas are all involved in motor-, coordination-, recognition- and memory tasks. These are definitely cognitive abilities that are essential for the reading of musical scores. However, the involvement of the suggested regions in these more general cognitive processes indicates that the music reading sites are not exclusively involved in music reading. More likely the several areas process the coded information of the score bit by bit with use of their more basic function, leading to comprehension of the music and musical output on the musicians instrument. The neural areas therefore probably work together in a score-reading network, which is lateralized mainly to the left side of the brain.

Also the research addressing the comparison between music- and language processing is reviewed, with a focus on a possible overlap of the two types. Single-case studies revealed that the areas that process music and language mostly not show overlap, but are separated. In the light of the findings on lateralization and localization this is an interesting observation since the language processing areas are apparently not located in the general cognitive skills areas just discussed for music reading, and language processing obviously needs recognition- and working memory skills too. Studies on the overlap of music- and language reading in the brain are scarce, especially neuroimaging literature on the subject is rare. The present neuroimaging data suggest that the intraparietal sulcus and the middle temporal gyrus were only active in score reading, and the frontal gyri, the supramarginal gyrus and the posterior part of the superior temporal gyrus are active in both. However, the data for the music-specific areas were more commonly found.

For the epileptic violinist that will be under surgery in the UMC Utrecht in a few months, it is advisable to define the dominant parietal lobe, the occipito-temporal lobe and the frontal gyri by electrocortical stimulation before surgery. These regions are most commonly found in music reading research. Roux even explicitly mentions the importance of a score-reading task in addition to standard language tasks in musicians who undergo direct brain mapping for epilepsy surgery, in particular in the dominant parietal lobe (Roux *et al.*, 2007)

Concluding, in reviewing the available studies on the subject it became evident that this field of study is underdeveloped and needs further investigation, especially in neuroimaging. Since a noticeable part of the literature still consists of single-case studies from longer than ten years ago, this interesting subject is in need of new, reliable insights.

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