



Research article

“Neural differences in expert guitarists during over-learned non-standard visuomotor mapping of abstract versus concrete information”

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ABSTRACT

Using visual information to perform actions is a fundamental aspect of human behavior. Musicians commonly translate visual information into action using both concrete and abstract visual information. We exposed expert guitarists to four types of familiar visual depictions of action instruction including musical notation (very abstract), tablature (abstract), chord diagrams (more concrete), and actual pictures of guitars chords being formed (very concrete). These were shown during fMRI scanning as the guitarists formed the appropriate chords (as visually depicted) on a magnet safe guitar fret board with strings, or where they simply viewed the visual stimuli without an action. Whole brain contrasts revealed that the right precuneus was more active for abstract instruction while an occipito-insular circuit was more active for concrete instruction. The current findings highlight that the degree of over-learned visual abstraction is an important factor modulating visual-motor processing.

1. Introduction

We use vision and action in tandem to complete everyday tasks - from grabbing a cup of coffee, driving to work, or playing a musical instrument. This involves sensorimotor mapping. There is a difference between standard and non-standard sensorimotor mapping [1–3]. Standard visuomotor mapping refers to when a visual object or visual information is both the guide and the target of action (e.g. seeing a coffee cup and grasping it by the handle). Work on standard visuomotor mapping highlights the differences between the dorsal and ventral visual streams that relate to *how* to perform visually guided actions versus *what* is visually perceived, respectively [4]. There are also cases in which there is an arbitrary or associative relationship between visual information and the action it cues (e.g. seeing an empty coffee cup and turning on the coffee-maker). This has been referred to as non-standard visuomotor mapping, conditional motor behavior, or arbitrary visuomotor mapping [1–3]. This type of mapping is the focus of the current work.

Standard and non-standard visuomotor mapping derive from disparate neural regions and/or networks [1,2,5,6]. Lesion work has shown that the premotor cortex [2] and prefrontal cortex [7] appear to be utilized during both the formation and execution of arbitrary or non-standard visuomotor associations. Neuroimaging research also

supports the importance of these regions, and others such as the basal ganglia, for non-standard visuomotor mapping [8]; [5,9]. One PET study demonstrated that non-standard visuomotor mapping (i.e. conforming the hand to a particular shape based on a visual cue) involved the recruitment of dorsal precentral areas and striatal regions whereas standard visuomotor mapping (i.e. grasping an object) uniquely led to activation in the parietal cortex [5]. Using fMRI, Gorbet & Sergio [10] found that non-standard motor mapping was distinguished from standard motor mapping in several sensorimotor areas using multivoxel pattern analysis. While these differences occurred for recently formed visuomotor associations, other studies have shown that the parietal lobe regions of the dorsal visual stream may become involved in the translation and execution of non-standard visuomotor associations when such associations are highly overlearned [11]; see also [12] for related behavioral evidence). The current study evaluated how changing visual information alters neural responses in the context of non-standard visuomotor mapping using a highly overlearned stimulus set.

Concrete visual information represents the environment in a more veridical manner, whereas abstract information is less veridical and more symbolic. A key aspect of abstract visual symbols is that they can reduce the amount of information necessary in a concrete stimulus. While there is some degree of overlap between the processing of abstract and concrete stimuli, there are also differences in the way these types of

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information are treated. Behavioral work has shown that abstract cues have differential effects on bimanual movements compared to concrete cues, and that abstract cues may take more time to translate than concrete cues [13]. Chouinard and Goodale [14] found that nonstand mapping of novel abstract visual stimuli into actions involved premotor, supplementary motor, cingulate, intra-parietal sulcus, and thalamus. Similarly, Vogt et al. [15] found inferior parietal, premotor, and frontal involvement during the viewing and imitation of video clips of hands playing guitar chords. Studies have also implicated the cerebellum as playing a crucial role in the translation of abstract visual information into actions [16,17].

Our goal was to further explore how the brain processes differences in abstractness/concreteness during the translation of vision to action during non-standard visuomotor mapping by examining it with an over-learned behavior. We wanted to extend previous work by using very different stimuli and motor tasks. Furthermore, the design of the current study is unique in that we are able to investigate translation of vision to action across different levels of visual abstraction while comparing this to passive watching of the same stimuli alone.

We recruited expert guitarists because they commonly use at least four distinct types of visual information to execute complex non-dominant hand movements such as fretting chords (three or more individual notes that are played simultaneously). We focused on four types of symbols that guitarists commonly use to fret chords - musical notation, guitar tablature, guitar chord diagrams, and actual images of guitar chords being fretted. These symbols vary in their veridicality or the degree to which they resemble the actual action to be taken. Pictures of a guitar strings with a hand fretting a chord is a concrete representation of the desired action. Chord diagrams are less concrete, but are still interpretable by a novice, because they are a schematic representation of a guitar neck. Tablature diagrams are considerably more abstract, because they rely on symbols to reduce the amount of information. Because of this, a novice must spend time learn how to read this type of information fluently. Musical notation is extremely abstract, requiring expertise to translate the visual symbols into action. Additionally, we compared viewing without action to viewing with the action of placing fingers in the correct position to execute a guitar chord. We hypothesize based on previous work that non-standard motor mapping of more abstract stimuli would recruit fronto-parietal networks more than concrete stimuli. In contrast, we hypothesize that concrete stimuli would recruit ventral occipito-temporal networks more than abstract, as concrete stimuli contain more salient visual features.

2. Methods

2.1. Participants

Twelve male students, all but one from Indiana University's Jacob School of Music, participated in this study (mean age = 24.08 SD = 4.1), including 2 doctoral students, 4 master's students, and 6 undergraduates. The guitarists in this study had an average of 9.08 years of formal guitar training (SD = 1.92) and an average of 10.3 years of experience reading music notation (SD = 5.03). All participants starting playing guitar at an average age of 9 (SD = 4.1), and had a mean practice time per day of 5.1 h (SD = 1.3). Seven out of the 12 participants also play other instruments regularly. All participants reported right-handedness and normal or corrected-to-normal vision and gave informed consent according to the guidelines of the Indiana University institutional review board. Participants were compensated for their time.

2.2. Stimuli and apparatus

Experimental runs included visual symbols that we classified into four categories based on the level of abstraction required to translate the symbolic information into a motor action. Symbolic representations of

the actions required to play a guitar chord were shown to the participant in the forms of: Music notation (Fig. 1a), guitar tablature (Fig. 1b), chord diagrams (Fig. 1c), and a black and white photograph of a guitarist's hand forming each chord (Fig. 1d). Musical notation provides no definite physical or spatial information about where or how to place fingers on guitar strings, and communication of pitch is arbitrary. No concrete physical characteristic of an instrument requires a specific pitch to be in a specific position on a musical staff; therefore, notation can be used for any number of instruments. The expertise of our participants likely meant that notation was also the most common stimulus currently used by our participants. The second type of representation, guitar tablature, also utilizes horizontal lines (similar to notation) but includes numerical information that specifies the spatial information required (which of the 6 strings and the exact fret) to correctly play a chord (Fig. 1b). Although this type of symbolic representation provides specific spatial information of where to place the fingers on the fret board, it does not provide a representation of the guitar fret board itself. The third type of representation, guitar chord diagrams, consist of a simplified line drawing of a guitar fret board with dark circles on the strings indicating where a guitarist should place his/her fingers (Fig. 1c). These stimuli provide both specific spatial information as well as a two-dimensional representation of a guitar fret board itself, and is therefore, more concrete than the tablature. Finally, photographs of a guitarist's hand on a fret board were used as a more veridical representation of the required action, and were therefore considered more concrete than the other stimuli (Fig. 1d). Thus, the visual stimuli used are all symbols that convey the same information to a guitarist, but with varying levels of abstractness.

All visual stimuli were presented in black and white to obtain color consistency across all stimuli. The chords presented were all major and minor ranging from A Major to G Major. G minor and C minor chords were removed from the study because of the physical limitations of the apparatus. The apparatus used in the MRI was an actual guitar fret board that was modified to be MRI safe and resized to fit in the bore of the magnet (See Fig. 1e for picture).

2.3. Pre-scan procedure

Prior to entering the imaging facility, participants went through a testing process to evaluate their ability to perform the task. First, in a practice session outside the MRI simulator, the participants were observed viewing all stimulus types and performing the appropriate chord forms on the MRI safe guitar fret board to determine whether they could properly execute the task. Once the experimenter determined through observation that they could read and play all stimuli, they practiced the task in an MRI simulator to ensure that they were comfortable playing chords in this type of environment (they could not look at their hands). We ensured participants could play the chords correctly in the time provided across all four stimulus types to 100 % accuracy.

2.4. MRI session

2.4.1. Experimental design

The experiment contained four experimental runs and a high-resolution anatomical scan. Each experimental run consisted of 8 blocks of stimuli, 4 of which were 'watch' conditions, and 4 were 'play' conditions. We used a block design to decrease task switching and overlapping of the BOLD response. Within each run all stimulus types were presented twice (once as a 'watch' condition and once as a 'play' condition). The order of watch and play blocks were pseudo-random. Within each block only stimulus of one category of abstractness were presented - that is, there were separate blocks for notation, tablature, diagrams and photographs. Thus, both task (play or watch) and stimulus type were within-run conditions. Within each 32 s block, each visual stimulus was presented for a total of 1.5 s, with a .5 s fixation period, resulting in a total of 16 stimulus presentations per block. In a given

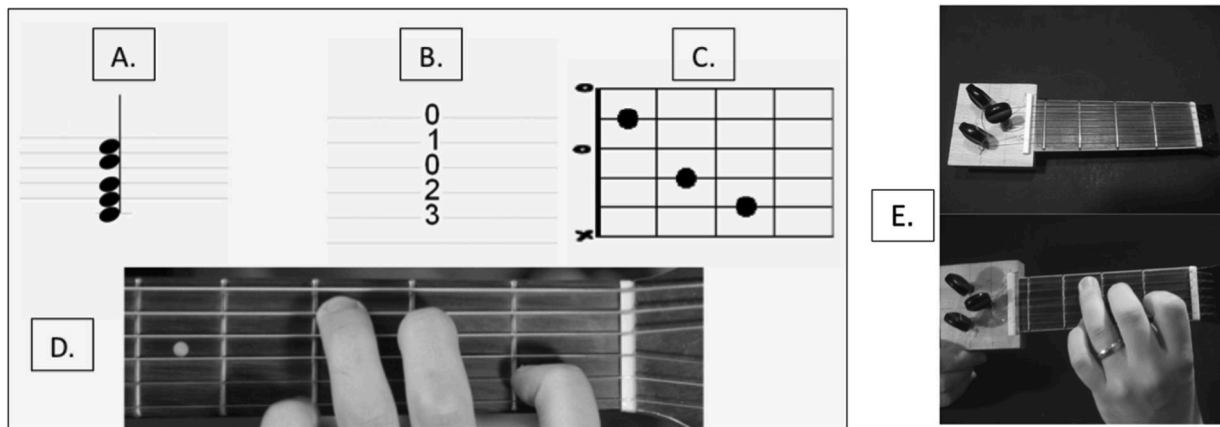


Fig. 1. A–E Examples of the visual stimuli that were presented in the main runs of the study. The above stimuli show representations of a C major chord. Figure 1E shows an example of the MRI safe guitar fretboard with nylon strings.

block, 16 separate guitar chords were presented - 12 unique chords, 4 repeated. This let us ensure all chord forms were presented in each block. The presentation of the chords was pseudo-random. The repeated chords were also pseudo-random, but stayed consistent throughout each category of stimuli. Between blocks a rest period of 12 s was included with a blank background and fixation point, resulting in runs that lasted 5 min and 56 s. In the last two seconds of the rest period, two seconds prior to the start of a block, the instruction word ‘play’ or ‘watch’ was displayed on the screen in order to indicate to participants whether a block involved playing chords or simply viewing them, respectively. Finally, a 7-minute high resolution anatomical whole brain scan was given at the end of the fMRI session.

2.4.2. Procedure

Eligible participants returned to the laboratory within one week of the pre-scan session and were given instructions and safety screening prior to completing the fifty-minute scan. The participants were asked to play or watch each block prior to the start of the block. ‘Playing’ consisted of forming the chord with their left hand while keeping their right hand still. Participants were instructed to form the chord as quickly and accurately as they could when the visual stimulus was presented and hold the chord until the next visual stimulus with a new chord appeared. During the watch conditions the guitarist was asked to hold both of their hands still while paying attention to the visual information of the chords being presented to them. The participants right hand would remain at their side, and their left hand would remain gripping the fretboard but motionless. An experimenter watched to ensure that the participants were not moving their fingers during ‘watch’ conditions, and were ‘playing’ during the play conditions - this was confirmed by an MRI safe video camera placed within the MRI environment. Two runs from 2 different participants had to be excluded from analysis because participants were playing when asked to watch, and watching when asked to play.

2.5. Functional imaging parameters

Imaging was performed using a 3-T Siemens Magnetom Trio whole body MRI system and a 32-channel head coil, located at the Indiana University Psychological and Brain Sciences department. All stimuli were back-displayed via a Mitsubishi XL30 projector onto a screen that was viewed through a mirror from the bore of the scanner. Stimuli were presented via Superlab version 4 software via an Apple Macbook laptop.

The field of view was $22 \times 22 \times 9.9$ cm, with an in plane resolution of 64×64 pixels and 33 slices per volume that were 3.4 mm thick. These parameters allowed us to collect data from the entire brain. The resulting voxel size was 1.7 mm x 1.7 mm x 3.4 mm. Images were

acquired using an echo-planar technique (TE = 28 ms, TR = 2000 ms, flip angle = 70°) for BOLD based imaging. High-resolution T1-weighted anatomical volumes were acquired using a 3D Turbo-flash acquisition.

2.6. fMRI data analysis

BrainVoyager QX 2.3 (Brain Innovation, Maastricht, Netherlands) was used to analyze the fMRI data. fMRI preprocessing included slice scan time correction, 3-D motion correction, Gaussian spatial smoothing with a FWHM of 6 mm, and linear trend removal. Individual anatomical volumes were normalized to the stereotactic space of Talairach using eight-parameter affine transformation, with parameters selected by visual inspection of anatomical landmarks. Applying the same affine transformation to the co-registered functional volumes placed the functional data in a common brain space, which allowed comparisons across participants. Voxel size of the normalized functional volumes was re-sampled at 3mm^3 using trilinear interpolation. Cluster threshold size was set to this voxel size. Brain maps in figures are shown with the voxel size re-sampled at 1mm^3 .

The data for the experimental runs for all participants were analyzed with a random effects general linear model. Predictors in the model were time-based functions for each experimental condition with condition intervals modeled as delta functions and then convolved with a two-gamma HRF. Regressors of no interest included the six raw motion estimates reported by the BrainVoyager motion correction procedure. When performing contrasts between conditions, we used the BrainVoyager Cluster-Level Statistical Threshold Estimator plugin (Goebel, Esposito, and Formisano 2006) to control for multiple tests. The plugin estimates the cluster-size threshold necessary to produce an effective $\alpha < .05$, given a specific voxel-wise p-value, using Monte Carlo simulation. The voxel-wise statistical threshold for all analyses was set at $p = 0.001$. For all analyses, the estimated cluster-level threshold necessary for correction was a size of 3 voxels (voxels were 3mm^3). Beta weights from significant clusters of BOLD activation were extracted using the VOI tables function in BrainVoyager. Anatomical labels for clusters were found using the Talairach daemon by entering the coordinates of the center of mass of each cluster.

In addition to “standard” contrasts, differences between all four levels of abstractness/concreteness were assessed using what we called a “linear weighted-contrast”. In this analysis, t-contrasts were computed for the four play and separately for the four watch conditions (Notation > Tablature > Diagrams > Pictures) with contrast coefficients of 2, 1, -1, -2, respectively. In this way, the positive tail of the contrast represented abstractness and the negative tail of the contrast represented concreteness.

3. Results

3.1. Main effect of playing vs. Watching

We contrasted all ‘play’ conditions with all ‘watch’ conditions. Not surprisingly, performing an action during the play condition recruited the sensory-motor cortices more compared to the watch condition (for cluster information see Supplementary Table 1). The bilateral precentral gyri, and left postcentral gyrus were more active during playing than watching. Medial regions including the claustrum, cingulate, and insula were also more active during guitar ‘playing’ than ‘watching’, as were the left superior frontal gyrus, the left fusiform gyrus and the left cerebellum. However, the watch condition recruited the right superior frontal gyrus, the left IFG, middle occipital gyrus, and middle temporal gyrus more than the play condition. The regions recruited during this contrast were heavily left lateralized, and included visual association regions, sensory and motor cortices and frontal regions.

3.2. Linear contrast for watch and play conditions

A linear-weighted contrast was performed to identify regions that followed an increasing recruitment depending upon degree of abstractness of the visual input. We first performed this analysis on the ‘watch’ conditions, in which the values (2, 1, -1, -2) were assigned to

produce the contrast Watch Notation > Watch Tablature > Watch Diagram > Watch Photographs (see Fig. 2A). For specific cluster information see Supplementary Table 2. Overall, increasing abstractness appeared to recruit the right precuneus. In contrast, more concrete cues increased recruitment of the right insula, right middle occipital gyrus, and right lingual gyrus.

We performed a similar contrast across the Play conditions where the values (2, 1, -1, -2) were assigned to produce the contrast Play Notation > Play Tablature > Play Diagram > Play Photographs (see Fig. 2B). This allowed us to identify regions that showed activation related to increasingly more abstract or concrete visual cues during the translation of vision to action in the play condition. For specific cluster information see Supplementary Table 2. Increasing the abstract nature of visual cues recruited the right superior parietal lobule, the left cerebellum, and the precuneus. Increasingly concrete visual cues recruited the right middle occipital gyrus, the right lingual gyrus, the right cuneus, the left superior frontal gyrus, the left cuneus, and the left parahippocampal gyrus.

To test the overlap of the linear contrasts for Watch and Play conditions directly, we conducted a conjunction analysis of the linear watch and linear play contrasts (see Fig. 2C). For specific cluster information see Supplementary Table 2. This analysis showed overlap for Play and Watch conditions in the right precuneus for increasingly abstract information. For Play and Watch conditions, increasingly concrete information was associated with overlap in the right lingual gyrus, left

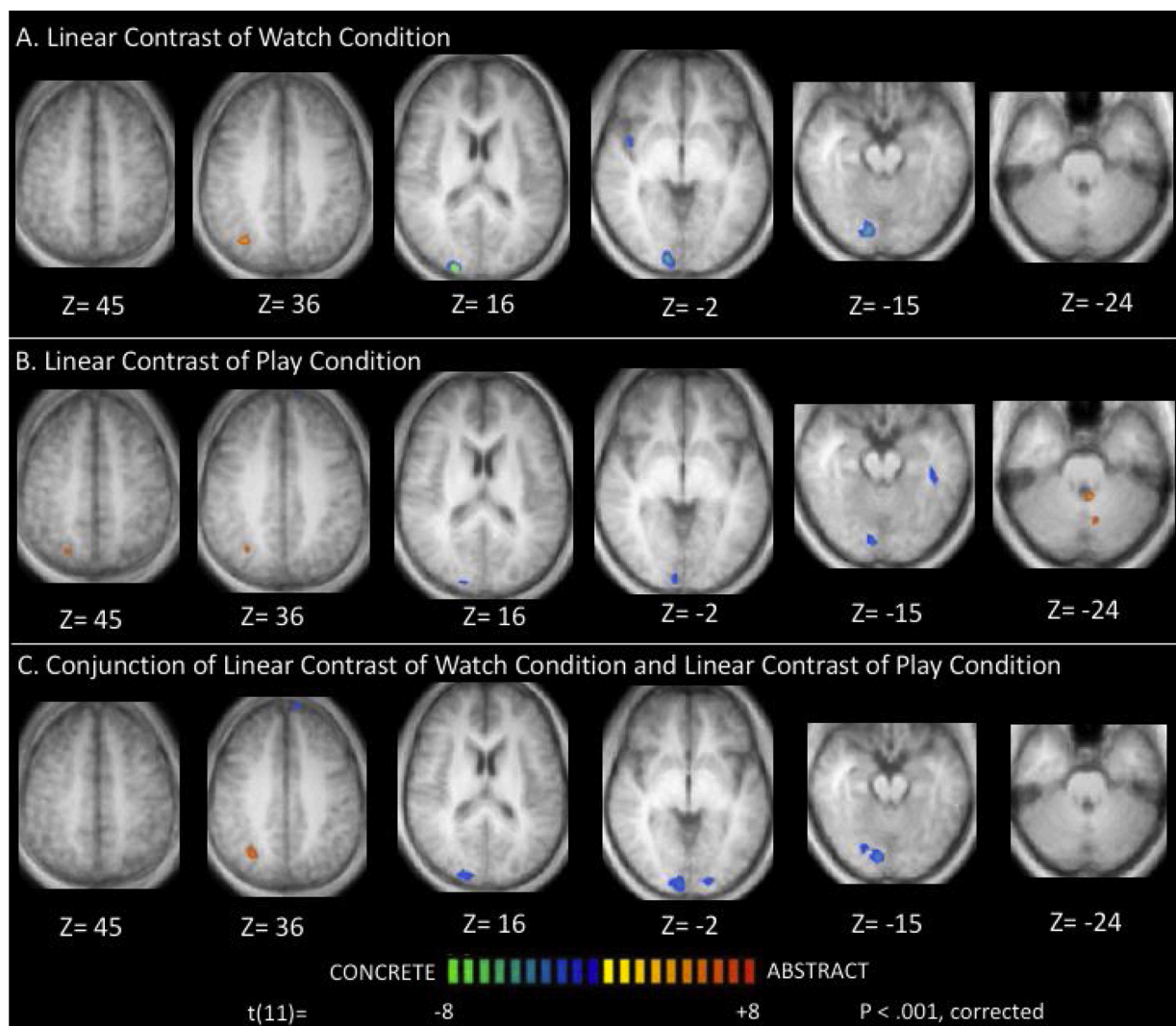


Fig. 2. A–C Results of the linear Watch and Play conditions and the conjunction of both.

cuneus, and the left superior frontal gyrus..

4. Discussion

This is the first study to document relative changes in BOLD responses, in the context of non-standard visuomotor mapping across multiple visual cues that differed in their degree of abstraction/concreteness. Both direct and linear-weighted whole brain contrasts showed that several diverse processing regions are modulated by the degree of abstraction/concreteness during both playing and watching of guitar chords.

4.1. Linear differences in playing and watching across levels of abstraction/concreteness

Linear contrasts allowed us to find regions that were modulated by relatively more abstract or concrete visual information during both the watch condition and the play condition. Results from these linear contrasts demonstrated that different networks of regions were active depending on the degree of abstraction/concreteness as well as whether the visual cues were watched without action or that were actively translated into chords on the guitar fret board.

During the Play condition a network that included the right superior parietal lobule, left cerebellum, and left precuneus was more active as the degree abstraction of visual cues increased. These three regions seem to be recruited for the translation of relatively more abstract than concrete symbolic cues into configural hand actions such as chords. This linear contrast also demonstrated that translating concrete visual cues to action was associated with greater activation in a different network of regions including right lingual gyrus, right middle occipital gyrus, left superior frontal gyrus, bilateral cuneus, left parahippocampal gyrus.

During the Watch condition, the right precuneus was uniquely more active as the level of abstractness increased. Several regions including the right insula, right middle occipital gyrus, right lingual gyrus were uniquely more active for more concrete cues during the Watch condition.

Regions that respond to increasingly more abstract visual information include those located in the dorsal visual stream. This includes the right superior parietal lobule that has also showed similar properties in previous work by [18]. In contrast, regions that respond to increasingly more concrete information were generally located in the ventral visual stream. As stated in the introduction concrete information generally includes more visual information and therefore we expect more processing to occur in the “what” pathways of the ventral visual stream.

Our results are similar in some ways to previous work on non-standard visuomotor mapping using linguistic [19] and nonlinguistic stimuli [20]. However, those studies found that abstract cues tended to activate left parietal and left premotor regions whereas we found similar regions that were right lateralized for abstract information. This could potentially be due to the fact that all of our participants were using their left hand. It could also be related to the musical nature of the stimuli.

4.2. Overall differences between play and watch conditions

When comparing all Play versus Watch conditions directly there was, as would be expected, greater activation in several motor-related regions for the Play than Watch condition (e.g. precentral gyrus, cerebellum). In contrast, there was greater activation in frontal, occipital and temporal lobe regions during the Watch than Play condition. This suggests that processing is different to some degree between the Watch and Play conditions beyond just motor regions being relatively more active due to actions being physically performed. In addition, attention could be allocated differently during the Watch and Play conditions. One possibility is that during the Watch condition participants may be performing motor, auditory, and visual imagery for example, in order to mentally rehearse the action and resulting sound from memory.

Previous work has suggested that stimuli associated with familiar actions automatically triggers affordance specification that is associated with greater activation of sensorimotor regions [21]. The watch condition could be interpreted as a ‘motor imagery’ condition, however, we have no way of knowing whether or not the participants were performing some sort of motor imagery. We were, however, assured that they were visually perceiving during the watch condition. We therefore, labeled this condition as ‘watch’.

4.3. Limitations

Expert guitarists were included in this study because they have the ability to use different types visual cues across multiple levels of abstraction in order to perform complex naturalistic actions while in the MRI environment. While this was a within-subjects design with a group that has specific expertise, 12 participants is a relatively low sample size. The fact that we only had male participants was not an intentional choice nor does it reflect a choice to exclude female participants. Ideally, we would have an even number of male and female participants. Previous studies have suggested that neural activation related to standard [22] and non-standard [23].visually guided actions may be different between male and female participants.

There are some potential limitations in the way we needed to define our four levels of abstraction given our use of naturalistic stimuli. The amount of information differs at each level. This difference might be inextricably tied to the amount of abstraction, but would be important to attempt to control for in the future. This level of stimulus control may require the use of novel stimuli that are less naturalistic. Without that level of stimulus control, we cannot rule out that the results could have been influenced by stimulus dimensions such as complexity, familiarity, and ‘objectness’. Also, because the stimulus types are categorical, we cannot claim that the actual differences in the level of abstraction between each of the four stimulus types are the same, that is, that the trend across the four categories is perfectly linear. For example, the difference between Tablature and Diagrams could be larger than the difference between Tablature and Notation. The level of control afforded by novel stimuli and a training paradigm would allow for more precise distancing of the categories along the abstractness/concreteness continuum. The actual image of a human hand playing the guitar may not represent the same perceptual processing as seeing a real hand and fretboard in three dimensional space. Notation may be the most common stimulus that is currently used by our participants while playing guitar. However, to ensure that all stimuli were equally ‘playable’, we had to use experts as participants, and that all stimuli were learned/played to equal degrees. We therefore tried to equate the behavior as much as possible while manipulating the stimuli. Based on the stimuli themselves, and not on the particular experiences of the participants, we feel that the most appropriate difference is in the abstract – concrete continuum.

The current study and future work would benefit from a control group of non-expert participants. Ideally future studies could include a group of naïve participants who learned to play guitar with all four stimulus types (including musical notation) and were tracked longitudinally, however, the feasibility of such a study is questionable. A less involved protocol would be to train naïve participants on only tablature and diagrams, which require considerably less expertise to effectively translate into action.

5. Conclusion

In conclusion, our results show for the first time that neural differences exist when guitarists play and watch abstract and concrete visual stimuli. Overall, the differences in brain activation when one is translating abstract versus concrete information into actions suggest that different types of visual-motor processing occur for these distinctive types of visual information. Therefore, the degree of abstraction/concreteness of visual information is an important factor that modulates

the translation of vision to action.

Declaration of Competing Interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.neulet.2021.135624>.

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