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The beauty of language structure: A single-case fMRI study of palindrome creation

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ABSTRACT

Humans seem to be inherently driven to engage in wordplay. An example is the creation of palindromes – sentences that read the same backward and forward. This activity can be framed as a curiosity-driven behaviour, in which individuals seek for information that serves no direct purpose and in the absence of external rewards. In this fMRI case study, an experienced palindrome creator was scanned while he generated palindromes with different levels of difficulty. Palindrome creation was alternated with resting periods and with a working memory task, both serving as control conditions. Relative to resting, palindrome creation recruited frontal domain-specific language networks and fronto-parietal domain-general networks. The comparison with the working memory task evidenced partial overlap with the multiple-demand cortex, which participates in solving a variety of cognitively challenging tasks. Intriguingly, greater difficulty during palindrome creation differentially activated the right frontopolar cortex (BA 10), a region that was also linked to palindrome resolution. The latter is consistent with exploratory behaviour – in this case, with seeking new but interdependent linguistic segments within a complex internal model (i.e., a palindromic structure)– and bears resemblance with brain substrates sustaining hard logical reasoning, altogether pointing to a commonplace for curiosity in discovering new and complex relations.

1. Introduction

The discovery of language and its socio-cultural evolution (Everett, 2012) has conferred humans the most powerful communication device, which has preceded other cultural innovations. Although language is usually analysed in terms of its functional role, less is known about the attraction that formal aspects of language exert in humans – some individuals just seem to feel an intrinsic pull to use language in terms of play or exploration, or, in Maslow's words (Maslow, 1963), for "pure cognizance motives", as is evidenced in

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behaviours like playing with the sound of words or their meanings (Crystal, 1998; Sherzer, 2010).

An aspect of language that has traditionally evoked wonder and joy in humans is its structure. A case in point is the existence of groups like the popular *OuLiPo* (*Ouvroir de Littérature Potentielle*), founded in the 1960s by French writers and mathematicians devoted to the “seeking of new structures and patterns” by applying certain rules or “constraints” to writing and literary creation. One of these interesting pursuits is the creation of *palindromes* – sentences or paragraphs that are the same when read forward and backward, letter by letter (Bergerson, 1973). For example, “*A man, a plan, a canal, Panama*” or “*Live time, never even emit evil*”, by Leigh Mercer. The beauty of these constructions lies on their symmetry –a property whose pursue is well-documented in other scholar disciplines (Chuquichambi, Corradi, Munar, & Rosselló-Mir, 2021; Golubitsky & Stewart, 2003, p. 325; Jacobsen, Schubotz, Höfel, & Cramon, 2006; Müller, 2003; Sasaki, Vanduffel, Knutsen, Tyler, & Tootell, 2005) (but see (Leder et al., 2018))–, as the sentences’ structure and meaning are the same from left-to-right and from right-to-left. In the case of transparent languages (i.e., one-to-one mapping between phonemes and graphemes), like Spanish, this bidirectionality works not only in print form but also in sound, as in “*Sapos, oíd, el rey ayer le dio sopas*” by Jorge Luis Borges. Although certain shortcuts can be applied to come up with simple palindromic structures, creating novel and meaningful palindromes is an effortful and demanding cognitive activity that requires time, concentration, and perseverance, and that is usually achieved only by experienced creators. For these devoted individuals, this is such a thrilling activity that they have founded palindrome creation groups, which have recently caught the attention of a broader audience through the release of documentaries like “*Viva el palindromo*” (Lipgot, 2018) or “The palindromists” (Clemente, 2020).

At the psychological level, one might wonder what drives humans to submerge themselves in this challenging linguistic game that has no apparent instrumental value. To a certain degree, the creation of palindromes might be mediated by curiosity, defined as an intrinsic motivation to learn and to seek new information (Gottlieb, Oudeyer, Lopes, & Baranes, 2013; Sharot & Sunstein, 2020), in the absence of foreseeable external rewards or advantages(Ainslie, 2013; Blain & Sharot, 2021; Ryan & Deci, 2000). It has been proposed

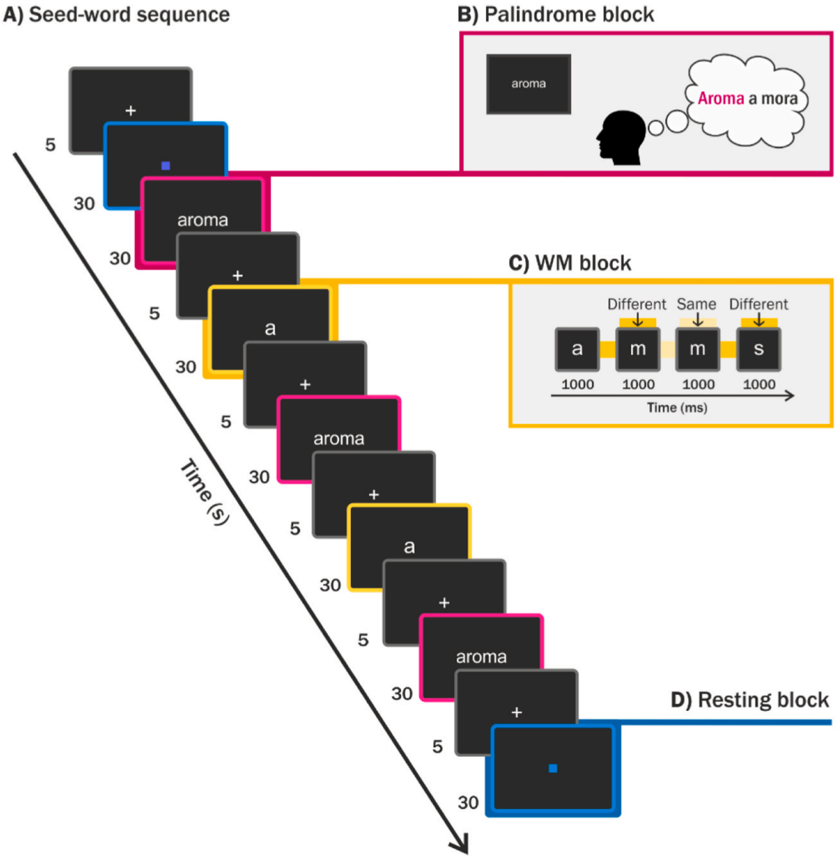

Fig. 1. Illustration of the experimental task. A) Schematic representation of the block sequence for one seed-word. This structure was repeated three times within a run, one for every seed-word. A fixation cross (5 s) announced the onset of the seed-word sequence. After a Resting block (framed in blue), TL created palindromic sentences with the given seed-word (e.g., *aroma*) in three Palindrome blocks of 30 s (framed in pink), and blocks of WM task (framed in blue) were interleaved. The coloured frames are only for illustration purposes. **B)** Palindrome block. The seed-word (e.g., *aroma*) was displayed in written format and TL covertly generated palindromic sentences (e.g., ‘*aroma* a mora’) for as long as the word remained on screen (30 s). **C)** WM block. Schematic example of the 1-back task in which TL indicated whether two consecutive letters were different (e.g., “a”, “m”) (left button press) or the same (e.g., “m”, “m”) (right button press). Each letter remained on screen for 1 s. **D)** Resting block. A blue square was displayed at the centre of the screen, and TL was instructed to simply stare at it.

that curiosity-driven information seeking might serve at least two functions: to reduce the uncertainty about the external world, and to elicit positive feelings (i.e., savouring) (van Lieshout, de Lange, & Cools, 2020). In the beforementioned documentaries, palindrome creators expressed feeling as though their brain is always in "active exploration" or in "search mode", trying to find words or phrases to complete unfinished palindromes or to create new ones. They also describe experiencing positive emotional states including absorption (Jamieson, 2005), which is characterized by extreme focusing, flow, and elation, and aesthetic feelings, such as a feeling of wonder, when they succeed in producing a new palindrome. These emotions and feelings could bear resemblance with those experienced during storytelling and the creation of narratives (Oatley, 2016; Oatley, Dunbar, & Budelmann, 2018), as well as to aesthetic experiences described in other artistic domains, like visual arts or music (Ferreri et al., 2021; Skov, 2019). Further, well-developed long-term interests are characterized by positive feelings and increased stored knowledge, creating added value for maintaining certain behaviours needed for achieving constructive and creative endeavours (Hidi & Renninger, 2006) (for example, see [Loewenstein, 1999] for an insightful analysis about Mountaineering passion).

Neurobiologically, curiosity-driven activities may be sustained by mechanisms involved in reward processing, as in the case of intrinsically regulated word learning (Ainslie, 2013; Bjork, Dunlosky, & Kornell, 2013; Gruber, Gelman, & Ranganath, 2014; Gruber & Ranganath, 2019; Hidi & Renninger, 2006; Ripollés et al., 2014, 2016). Specifically, participants who learnt the meaning of new words on their own –by exploiting semantic information from sentence contexts–, showed activation in mid-brain and ventral striatum reward processing regions, the same regions that are involved in processing external rewards (e.g., money or food) (Ripollés et al., 2014). Besides subcortical circuitry, the prefrontal cortex (PFC) might also be recruited when individuals seek information to satisfy their curiosity. In a decision-making task known as the "exploration-exploitation dilemma", the more rostral areas of the PFC (frontopolar [FPC] or rostro lateral prefrontal cortex; BA 10 and BA 46) showed greater activation when participants made explorative rather than exploitative decisions, the former helping them gain novel information instead of sticking to known options (Daw, O'Doherty, Dayan, Seymour, & Dolan, 2006). Accordingly, the PFC –which is known to be involved in high-level cognitive control–, might play a role in monitoring exploratory behaviour, for example, by computing and tracking the level of uncertainty during goal attainment (Frank, Doll, Oas-Terpstra, & Moreno, 2009).

To contribute to our understanding of the cognitive and neural basis of curiosity-driven behaviours, we present a single-case fMRI study revealing brain activation patterns during palindrome creation. An experienced palindrome creator, named TL, was asked to generate as many palindromic sentences as possible with given *seed-words* – words used as the starting point for the creation of palindromes (see Fig. 1). For example, the word *aroma* can be used as the seed-word to construct the palindrome "*Aroma* a mora"). Half of the seed-words entailed a higher difficulty, so that we could capture the cognitive effort associated with the effort of creating palindromes. During the experiment, TL alternated palindrome creation with periods of resting and with the performance of a simple WM task (*N*-back task), both activities serving as control conditions.

2. Methods

2.1. Participant

TL was a healthy, 40-year-old, left-handed, native Spanish speaker with higher education. He was also an English and Portuguese speaker (self-reported intermediate level in both languages). TL had been a palindrome creator for about thirteen years. When asked about his motivations to pursue palindrome creation, he expressed "overcoming the challenge", "the reward of succeeding" and "passing time". He did not report any neurological or psychological problems. The experiment was approved by the local ethics committee and TL signed a written consent before participating, in accordance with the principles of the Declaration of Helsinki.

2.2. Procedure

Before the scanning session, TL was given a short explanation of the scanning procedure and of the experimental task. He was shown pictures of the example stimuli and was briefed on the importance of minimizing head movement during the scanning session. After clarifying the procedure, the technician led TL into the scanner, where he laid in supine position and held the response box with his left hand, which rested on his belly. After completing the experiment and exiting the scanner room, he completed a surprise pen-and-pencil recall test in which he wrote down the palindromes that he had managed to create inside the scanner.

2.3. Stimuli

An expert palindrome creator (author AG) generated a list of 24 seed-words, that is, words to-be-used as the starting point to form palindromic sentences. The initial list contained words that the expert judged to be undoubtedly "easy" or "difficult" (half of each category). For example, the word *aroma* can be easily used as a seed-word to create the palindrome "*Aroma* a mora" (e.g., in English, "rat" for "Was it a rat, I saw?"). In turn, seed-words that were judged as "difficult" were words that, when reversed, led to infrequent or grammatically incorrect letter sequences, thus making it harder (or even impossible) to continue the sentence meeting the constraint on structure (e.g., *inope* in Spanish). To gain consensus about the categorization of the words, we asked another 6 expert palindrome creators from the *Club Palindromista Internacional* (http://cpalindromistai.blogspot.com/) to rate each seed-word in terms of its difficulty. Specifically, they were asked to assess how likely was each word to be included in a palindromic sentence with semantic meaning (1 = very likely, 5 = very unlikely). Based on their ratings, we selected a final set of 12 seed-words: 6 seed-words with lower mean scores (easy condition) (mean = 0.67; variance = 0.09) and 6 seed-words with higher mean scores (difficult condition) (mean =

3.83; variance = 0.29). In addition, if two seed-words had equal mean scores (e.g., *inope* and *oportuno*), we selected the one with the minimum variance (0.095 for the selected word *inope*, and 1.87 for the discarded word *oportuno*), taken as reflecting greater consensus among the experts. The final list of seed-words for the "easy" condition was *aroma*, *sol*, *avellana*, *deseo*, *miel*, and *mocita*, and, for the "difficult" condition, *inope*, *burro*, *recicla*, *fisión*, *mecánico*, and *pulmón* (for the full list of seed-words, see Supplementaty Materials).

2.4. Experimental design

The fMRI experiment had a blocked design with 3 conditions: 1) the main experimental condition in which TL covertly generated the palindromic sentences (Palindrome; Pal), and two control conditions, 2) a Resting (Rest) condition and a 3) Working Memory (WM) condition, a verbal 1-back task that required indicating whether two consecutive letters were the same (e.g., "a", "a") or different (e.g., "a", "b"). The Pal > Rest subtraction allowed to reveal the main brain networks associated with palindrome creation. In turn, the Pal > WM minimized the contribution of the multiple demand cortex (MDC), which participates in solving different types of cognitively challenging tasks (Duncan, 2010; Fedorenko, Duncan, & Kanwisher, 2013), thus allowing a better assessment of the involvement of domain-specific language-related networks.

In the experiment, a total of 12 seed-words (6 easy and 6 difficult) (for the selection criteria, see Section 2.3) were presented across 4 runs. Each run contained 3 different seed-words (e.g., *aroma*, *deseo*, *mecánico*). Odd-numbered runs (1 and 3) contained 2 easy and 1 difficult seed-words, and even-numbered runs (2 and 4) contained 2 difficult and 1 easy seed-words. Within runs, the order of the seed-words was randomized. TL was given a total of 90 s to covertly create palindromic sentences with each seed-word (*aroma*) (Fig. 1A), divided in three blocks of 30 s. These three blocks of palindrome creation were completed in sequential order and, in between them, TL performed the WM task, also in blocks of 30 s. In addition, before and after the Palindrome and WM blocks, he completed Resting blocks. In short, every seed-word was presented within the following sequence of blocks (of 30 s each) (Fig. 1A): Resting, Palindrome (first presentation), WM, Palindrome (second presentation), WM, Palindrome (third presentation), Resting. This structure was repeated three times in every run (one x seed-word).

More specifically, the task proceeded as depicted in Fig. 1A. Each run started with a fixation cross (5 s) that announced the beginning of a Resting block, in which TL stared at a small blue square for 30 s. Then, the seed-word (e.g., *aroma*) was presented in written format (Fig. 1B) and TL was instructed to covertly create as many palindromic sentences (of at least 4 words) for as long as the seed-word remained on screen (30 s). After that, a fixation cross was presented (5 s) and a WM block ensued (30 s) (Fig. 1C). The WM task was a 1-back task, in which he had to monitor a sequence of 20 letters, presented one at a time (1 s x letter), and indicate, using a button box held in his dominant hand, whether two consecutive letters were the same (e.g., "a", "a") (right button press), or different (e.g., "a", "e") (left button press). The letters were presented in pseudorandom order to avoid three consecutive trials of the same type. After the WM block, a fixation cross ensued (5 s). Then, the same seed-word (*aroma*) was displayed again, and TL resumed creating palindromes with it (30 s). Next, he completed another WM block (30 s) and, after a fixation cross (5 s), he completed the third and last Palindrome block (30 s), thus amounting to an overall of 90 s creating palindromic sentences with the *same* seed-word. Finally, a blue square was displayed again, instructing him to rest (30 s) (Fig. 1D) before the beginning of the next seed-word sequence (with a new seed-word). There was a total of 3 seed-word sequences (i.e., the structure shown in Fig. 1A) in the run. All runs had the same structure (but contained different seed-words).

In the end, TL completed 36 Palindrome blocks (3 × seed-word; 9 × run), 24 WM blocks (6 × run), and 24 Resting blocks (6 × run). The total duration of the experiment was about 50 min, with short pauses (<1 min) between runs. After the scanning session, TL was given a paper with the list of the seed-words (in order of presentation) and was asked to write down all the palindromes that he recalled having created with each seed-word inside the scanner (Solved). In case he had been unsuccessful, he was told to explicitly indicate it (Unsolved).

2.5. fMRI acquisition

Scanning was performed on a 3-T Siemens Trio System. To acquire functional data, a gradient echo pulse sequence was used (32 transverse slices oriented along the anterior-posterior commissural axis; repetition time of 2 s; echo time of 30 ms; 3 × 3 × 3.5 mm voxels and 0.8-mm interslice gap). A high-resolution T1-weighted magnetization-prepared rapid acquisition gradient echo image was also collected (240 slices sagittal; TR = 2300 ms; TE = 2.98 ms; 1 mm isotropic voxels).

2.6. Behavioural data analysis

The performance in the WM task was analysed with customized scripts in MATLAB 2017b. We considered correct responses when the participant correctly detected target trials and rejected non-target trials. Trials in which he did not provide a response were considered invalid. We computed overall correct and error rates to obtain an overall estimate of the performance.

2.7. fMRI pre-processing and data analysis

Data were analysed applying standard procedures as implemented in Statistical Parametric Mapping software (SPM) (version SPM8) (Welcome Centre for Neuroimaging, University College, London, United Kingdom; https://www.fil.ion.ucl.ac.uk/spm/) running under MATLAB 2017b. The following pre-processing steps were completed: realignment, co-registration, segmentation, normalization, and smoothing. Images were first spatially realigned with respect to the first volume of the first run (Friston, Williams, Howard, Frackowiak, & Turner, 1996) to correct for head-movement artefacts. Then, the T1 was co-registered to the mean echo planar imaging (EPI) volume obtained in the previous realignment step. The co-registered T1 was segmented and the resulting flow fields with the deformation parameters were used to normalize the realigned EPIs to the MNI space. Finally, normalized EPI images were smoothed with an 8 mm FWHM Gaussian kernel (Gurtubay-Antolin, León-Cabrera, & Rodríguez-Fornells, 2018; Ripollés et al., 2016, 2014).

2.8. *Whole-brain analysis*

To identify the regions involved in palindrome generation, we conducted a whole-brain analysis. First, we computed linear contrast images to examine brain activation associated with the active tasks versus resting state, that is, (i) of palindrome generation (Pal > Rest) and of (ii) performing the WM task (WM > Rest). Then, we assessed the (iii) main effect of palindrome generation without the verbal WM component (Pal > WM). The results were thresholded at $p = .05$ FWE-corrected at the cluster level and a minimum voxel size of $k = 50$ voxels.

Additionally, within palindrome generation blocks, we examined the main effect of difficulty (Difficult > Easy) and of successfully resolving palindromic sentences (Solved > Unsolved). To compute the latter contrast, we classified all Palindrome blocks (regardless of difficulty) based on TL's offline report at the end of the scanning session. In this case, the results were thresholded at p uncorrected equal to 0.001 and a minimum voxel size of $k = 50$ voxels.

2.9. *Activation maps*

2.9.1. *Language association test map*

To provide complementary information, we examined to what extent language-related regions were recruited during palindromes generation, we downloaded the association test map (ATM) for 'language' from NeuroSynth, a platform for large-scale, automated meta-analysis of fMRI data (http://www.neurosynth.org; search performed and map downloaded January 23, 2021; including 1101 studies). An ATM informs whether activation in an area occurs more consistently with the term of interest. For example, the ATM for 'language' shows larger positive z-scores in regions that are activated in studies that mention that term compared to those that do not (https://neurosynth.org/faq/#q18). The ATM was downloaded with the default threshold using false discovery rate (FDR) criterion of 0.01 to correct for multiple comparisons. To visualize the degree of overlap, the map was thresholded at ±3 z-score and overlaid on the Pal > WM contrast (p FWE = .05 at the cluster level and a minimum voxel size of $k = 50$ voxels).

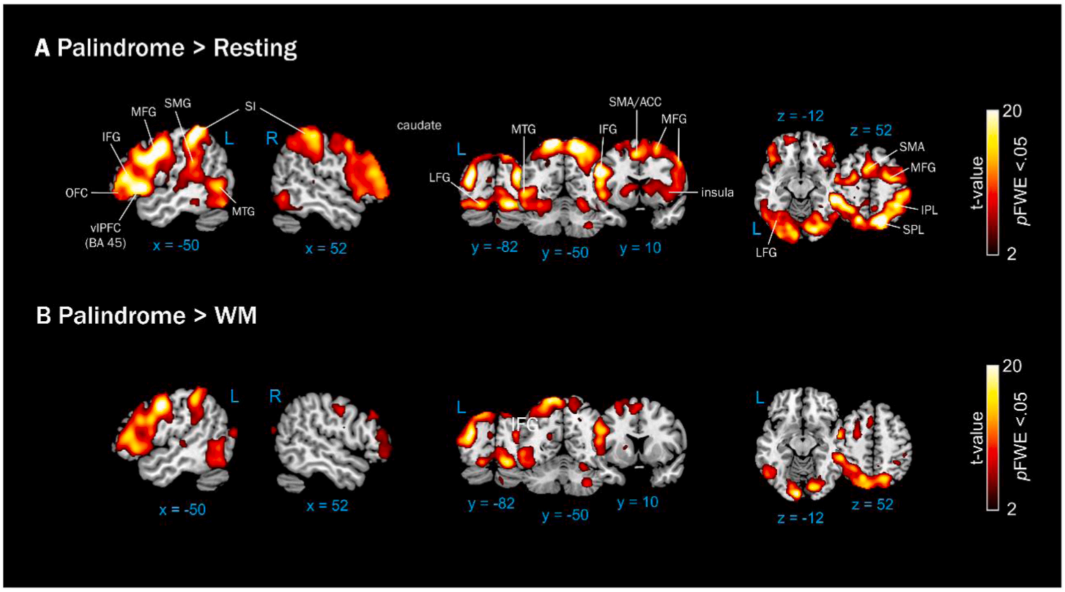

Fig. 2. Brain substrates of palindrome generation. A) Contrast showing the comparison between Palindrome and Resting. The main significant regions are labelled. Notice that the large increase in activation in the prefrontal cortex (MFG; IFG; OFC, vlPFC), most prominent in the left hemisphere, and bilaterally in the superior and inferior parietal cortex (IPL; SPL, STG), when the participant was generating palindromes. **B)** Comparison between the Palindrome and the WM task. For all contrasts, the main significant regions are labelled. Maps are thresholded at p FWE cluster-level = <0.05 and a minimum cluster size of 50 voxels. ACC, anterior cingulate cortex; IFG, inferior frontal gyrus; IPL, inferior parietal lobe; mOCG, middle occipital gyrus. MTG, middle temporal gyrus; OFC, orbitofrontal cortex; SFG, superior frontal gyrus; SI, primary somatosensory area; SMA, supplementary motor area; SMG, supramarginal gyrus; SPL, superior parietal lobe; STG, superior temporal gyrus; vlPFC, ventrolateral prefrontal cortex; vOT, ventral occipito-temporal; LFG; left fusiform gyrus.

2.9.2. MDC activation map

Similarly, we assessed the degree to which brain activation during palindrome generation overlapped with the MDC network, as represented in an open access activation map of the MDC network that is available at the MRC Cognition and Brain Sciences Unit website (https://imaging.mrc-cbu.cam.ac.uk/imaging/MDsystem; downloaded January 23, 2021). The map was originally obtained by averaging the activity from a variety of problem-solving tasks performed by (Fedorenko et al., 2013). The map was thresholded at $t > 1.5$ following the criteria used in the beforementioned study and overlaid on the t-map of the Pal > WM contrast (p FWE = .05 at the cluster level and a minimum voxel size of $k = 50$ voxels).

3. Results

3.1. Behavioural results

The overall percentage of correct responses in the working memory task was 85.4% (SD = 10.4%). Regarding TL's performance during the Palindrome generation task, he retrospectively reported creating a total of 12 palindromes (see **Supplementary Materials** for the complete list). He generated at least one palindromic sentence in trials with seed-words that were classified as easy (6 out of 6 trials), whereas he only managed to successfully create palindromes in one of the difficult trials (1 out of 6 trials). Therefore, there were a total of 7 "Solved" trials, and of 5 "Unsolved" trials, which were contrasted (Solved > Unsolved) to obtain the pattern of brain activity associated with successful palindrome generation (see Fig. 2).

3.2. fMRI results

3.2.1. Brain activation associated with palindrome creation

The main effect of palindrome creation (Pal > Rest) (Fig. 2A) revealed bilateral involvement of the dorsolateral PFC, including the left orbitofrontal cortex (OFC), left ventrolateral prefrontal cortex (vlPFC) comprising Broca's area (BA 45), the left inferior and middle frontal gyrus (IFG; MFG) and the supplementary motor area (SMA) ($p_{\text{FWE}} < .001$, $k = 308$, $\text{MNI}_{\text{peak-level}} = -14\ 56\text{–}14$, $t_{\text{peak-level}} = 11.09$). A large cluster of activation was found at bilateral superior and inferior parietal lobe (SPL; IPL; including the primary somatosensory area [SI] and the precuneus), bilateral middle and inferior occipito-temporal regions (mOCG and iOFG), bilateral caudate and right insula ($p_{\text{FWE}} < .001$, $k = 69544$, $t_{\text{peak-level}} = 31.35$, $\text{MNI}_{\text{peak-level}} = 16\text{–}64\ 60$). There were also smaller cluster at the right cerebellum ($p_{\text{FWE}} < .001$, $k = 140$; $t_{\text{peak-level}} = 8.28$; $\text{MNI}_{\text{peak-level}} = 42\ –44\ –44$) and right brainstem ($p_{\text{FWE}} < .001$, $k = 53$; $t_{\text{peak-level}} = 6.86$; $\text{MNI}_{\text{peak-level}} = 2\ –24\ –42$).

The activation pattern associated with palindrome generation without the verbal WM component (Pal > WM) (Fig. 2B) included

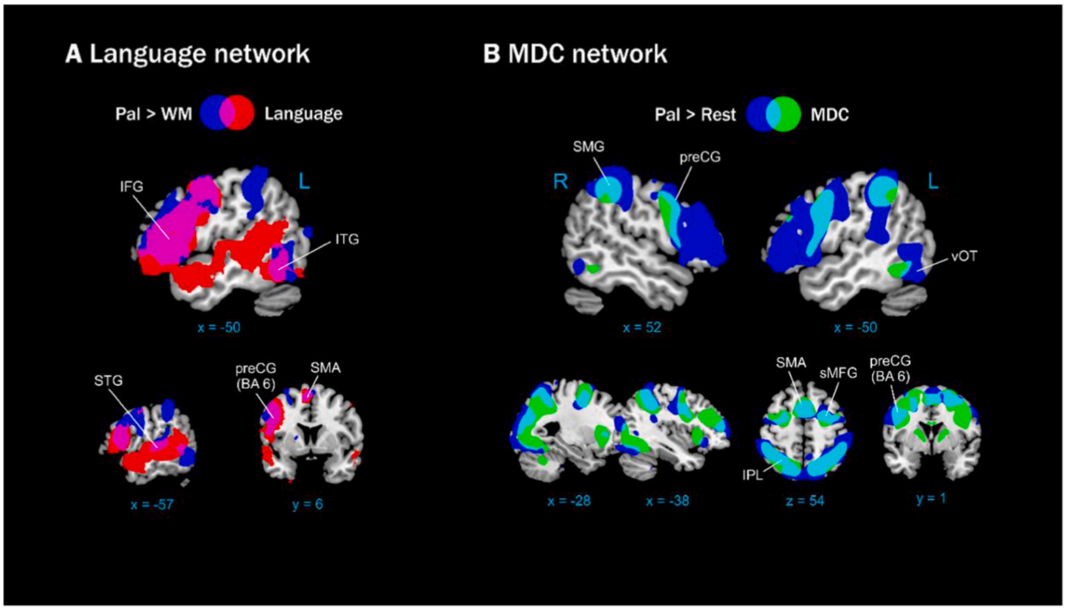

Fig. 3. A) Palindrome > WM contrast (thresholded at z-score ±6) overlaid on an association test map showing the regions more consistently activated for studies employing the term 'Language' (thresholded at z-score ±3). **B)** Palindrome > Resting contrast (thresholded at z-score ±8) overlaid on the activation map of the MDC network (thresholded at z-score ±1.5; as used by Fedorenko and colleagues (Fedorenko et al., 2013) in https://imaging.mrc-cbu.cam.ac.uk/imaging/MDsystem). IFG, inferior frontal gyrus; IPL, inferior parietal lobe; ITG, inferior temporal gyrus; lateral OG, lateral occipital gyrus; MFG, middle frontal gyrus; STG, superior temporal gyrus; preCG, precentral gyrus; SMA, supplementary motor area; sMFG, superior middle frontal gyrus; SMG, supramarginal gyrus; vOT, ventral occipito-temporal.

language-related regions in the left dorsolateral PFC during palindrome generation, including the MFG, the IFG and vPFC (BA 45, 47) ($p_{FWE} < .001$, $k = 5891$, $t_{peak\text{-}level} = 23.98$, $MNI_{peak\text{-}level} = -52\ -2\ 46$), but in this case it did not extend ventrally to the OFC. The activation pattern in the frontal lobe also included the left SMA encompassing both MFG and SFG (BA 6) and part of the cingulate gyrus (nearby the cingulate sulcus; BA 32) ($p_{FWE} < .001$, $k = 1571$, $t_{peak\text{-}level} = 14.02$, $MNI_{peak\text{-}level} = -2\ -4\ 66$) and, in the right PFC, activity increased at IFG (BA 46) ($p_{FWE} < .001$, $k = 364$, $t_{peak\text{-}level} = 8.45$, $MNI_{peak\text{-}level} = 56\ 36\ 12$) as well as medial ($p_{FWE} < .001$, $k = 142$, $t_{peak\text{-}level} = 8.42$, $MNI_{peak\text{-}level} = 30\ 56\ 10$) and superior regions of the right MFG (BA 9) ($p_{FWE} < .001$, $k = 205$, $t_{peak\text{-}level} = 8.36$, $MNI_{peak\text{-}level} = 52\ 30\ 36$). In the parietal lobe, the analysis showed a cluster in left ($p_{FWE} < .001$, $k = 11723$, $t_{peak\text{-}level} = 23.03$, $MNI_{peak\text{-}level} = -12\ -68\ 64$) and right IPL ($p_{FWE} < .001$, $k = 148$, $t_{peak\text{-}level} = 8.57$, $MNI_{peak\text{-}level} = 36–46\ 58$), right precentral gyrus (BA 6) ($p_{FWE} < .001$, $k = 585$, $t_{peak\text{-}level} = 13.92$, $MNI_{peak\text{-}level} = 58–4\ 40$), right cerebellum ($p_{FWE} < .001$, $k = 586$, $t_{peak\text{-}level} = 11.41$, $MNI_{peak\text{-}level} = 30\ -64\ -46$) and a large cluster located in superior and middle occipital regions that extended bilaterally to the lingual gyrus (BA 17, 18) ($p_{FWE} < .001$, $k = 4426$, $t_{peak\text{-}level} = 31.08$, $MNI_{peak\text{-}level} = -12\ -100\ 0$).

3.2.1.1. Palindrome generation (Pal > WM) overlap with language-related regions. Additionally, we further examined to what extent palindrome generation encompassed language-related regions by overlapping the main effect of palindrome generation on an association map representing the regions that are more consistently linked to language processing. To this end, we employed the Pal > WM contrast, as it minimized brain activity associated with domain general processes, thus providing a more constrained picture of the language-related regions involved in palindrome creation. As can be seen in Fig. 3A, and in accordance with the whole-brain analysis results (Pal > WM) (see Fig. 2B), generating palindromes engaged the left MFG and IFG, including Broca's area. It also recruited the left precentral cingulate cortex (preCG; BA 6) and supplementary motor area (SMA). Conversely, palindrome generation barely engaged ventral regions of the temporal lobe, such as superior temporal gryus (STG) and middle temporal gyrus (MTG).

3.2.1.2. Palindrome generation (Pal > Rest) overlap with the MDC network. Finally, we explored the degree of overlap between the activation pattern during palindrome generation (Pal > Rest) and the MDC (Duncan, 2010) (Fig. 3B). Note that, for this purpose, we employed the Pal > Rest contrast, rather than the Pal > WM, as the latter should largely subtract brain activity associated with the MDC. We found that there was substantial overlap at precentral and postcentral gyrus (SMA/ACC and superior MFG) and at parietal areas (IPL and SPL). On the other hand, the level of overlap was minor in the dorsolateral PFC, which was more extensively activated

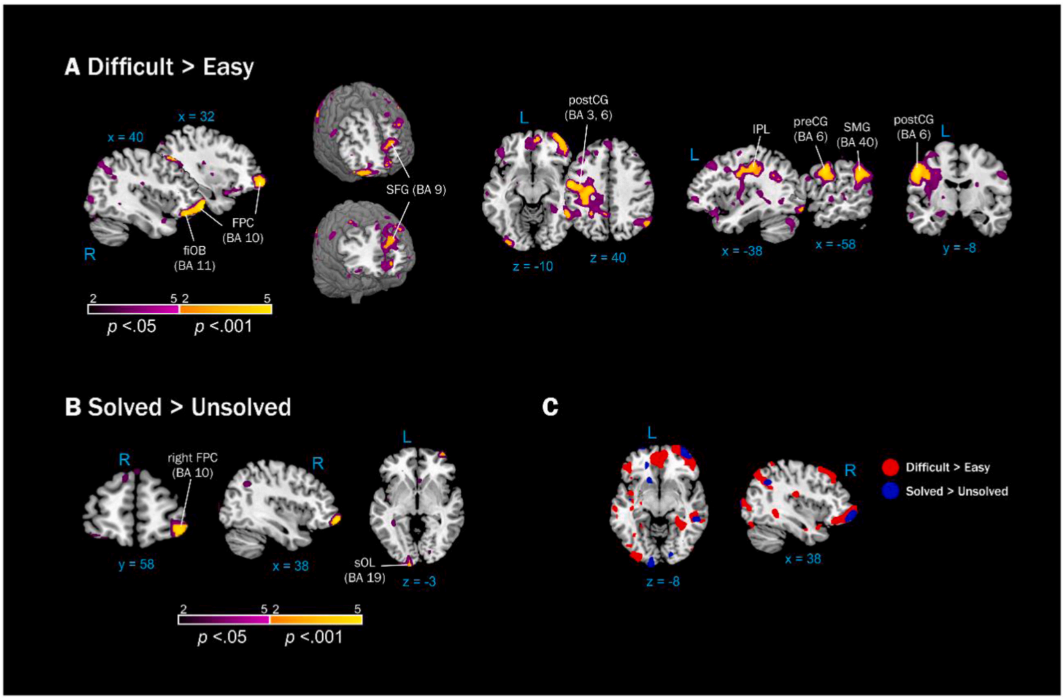

Fig. 4. **A)** Main activations when creating palindromes was more difficult compared to when it was easier as a function of the provided seed-word. Greater difficulty was associated with greater engagement of the right frontopolar cortex (FPC) and frontal inferior orbitofrontal cortex (fiOB), the left superior frontal gyrus (SFG), and lateral and medial left parietal regions (postCG, preCG, IPL, SMG). **B)** In those blocks in which the participant reported to have successfully generated palindromic sentences (Solved), there was greater involvement of the right FPC and the superior occipital lobe (sOL). **C)** Overlay of the Resolution effect (Solved > Unsolved) on the contrast of Difficulty (Difficult < Easy), showing that both mainly overlap at the right FPC cortex. Maps are thresholded at two different *p*-values uncorrected at whole-brain level ($p < .05$ in violet and $p < .001$ in yellow) and a minimum cluster size of 50 voxels. fiOB, frontal inferior orbitofrontal; FPC, frontopolar cortex; IPL, inferior parietal lobe; postCG, postcentral gyrus; preCG, precentral gyrus; SFG, superior frontal gyrus; SMG, supramarginal gyrus; sOL, superior occipital lobe.

during palindrome generation (MFG and IFG). There was also minor overlap at occipito-temporal regions, where brain activity associated with palindrome generation mostly involved lateral regions but did not extend medially through the lingual gyrus in the occipital lobe.

3.2.2. Effects of task difficulty and task resolution

We further explored brain activity as a function of the level of difficulty in generating the palindromes. When seed-words posed greater difficulties for palindrome construction (Difficult > Easy) (Fig. 4A), greater activation was found at the right PFC, including the right FPC (BA 10) and the frontal inferior orbitofrontal area (fiOB) (BA 11) ($p_{\text{uncorrected}} < .001$, $k = 593$; $t_{\text{peak-level}} = 6.44$; $\text{MNI}_{\text{peak-level}} =$ 38 60–2). There were also significant clusters at left SFG (BA 9) ($p_{\text{uncorrected}} = .003$, $k = 166$; $t_{\text{peak-level}} = 3.79$; $\text{MNI}_{\text{peak-level}} = -8$ 52 28), left precentral and postcentral gyrus (BA 3, 6) ($p_{\text{uncorrected}} < .001$, $k = 1331$; $t_{\text{peak-level}} = 5.57$; $\text{MNI}_{\text{peak-level}} =$ –54 –8 40), left supramarginal gyrus (SMG) (BA 40) ($p_{\text{uncorrected}} < .001$, $k = 377$; $t_{\text{peak-level}} = 5.87$; $\text{MNI}_{\text{peak-level}} =$ –62 –50 34), right IPL (partially over angular gyrus) ($p_{\text{uncorrected}} = .016$, $k = 95$; $t_{\text{peak-level}} = 3.98$; $\text{MNI}_{\text{peak-level}} =$ 54–64 38) and left cingulate gyrus ($p_{\text{uncorrected}} = .025$, $k =$ 81; $t_{\text{peak-level}} = 3.54$; $\text{MNI}_{\text{peak-level}} =$ –10 –48 28).

Lastly, we contrasted brain activity as a function of whether TL reported having successfully constructed palindromic sentences, or not (Solved > Unsolved) (Fig. 4B). Successful elaboration was associated with activation in the right FPC cortex (BA 10) ($p_{\text{uncorrected}} =$ .02, $k = 87$; $t_{\text{peak-level}} = 4.86$; $\text{MNI}_{\text{peak-level}} =$ 38 62–8). As shown in Fig. 4C, although overlapping, the frontopolar cluster associated with solving was more focal than that of the difficulty contrast.

4. Discussion

In the current single-case fMRI study, the brain of TL, an experienced palindrome creator, was scanned while he created palindromic sentences. To our knowledge, this is the first neuroimaging study uncovering the neural underpinnings of this ludo-linguistic activity. We found that palindrome creation lies on domain-specific networks involved in language processing in the dorsolateral and ventrolateral PFC (MFG; IFG, vlPFC), as well as on frontoparietal domain-general networks (IPL; SPL, STG), with partial overlap with the MDC. In contrast, language-related regions in the ventral temporal lobe, associated with semantic processing, were scarcely activated. Intriguingly, greater difficulty in creating palindromes was linked to activation in the right FPC (BA 10), a region that was also associated with successful palindrome resolution.

As in the case of other complex tasks, palindrome creation (relative to Rest) led to greater activation of frontoparietal domain-general regions known to be involved in high level control, as well as precentral and postcentral gyrus (SMA and superior MFG) typically linked to conflict detection and error monitoring (Paus, 2001; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). Relatedly, further analyses revealed substantial overlap with the MDC at parietal areas (especially the IPL, see Fig. 3B), a network that is engaged when solving novel problems or when performing complex tasks that require high cognitive control (Duncan, 2010). Further, in accordance with its verbal nature, palindrome creation (relative to WM) was associated with greater activation of the left dorsal frontoparietal network (MFG, IFG, including Broca's area), which is concerned with controlled linguistic processing, including, for example, controlled search and retrieval of semantic representations (Wagner, Paré-Blagoev, Clark, & Poldrack, 2001) and selection among competing candidates (Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). In contrast, however, creating palindromes did not differentially recruit ventral language pathway regions of the temporal lobe (superior and middle temporal areas) (see Fig. 3A), mostly involved in storage and access of lexical and semantic representations (Binder, Desai, Graves, & Conant, 2009; Lau, Phillips, & Poeppel, 2008). Of note, although most palindrome creators strive for a balance between structure and meaning, the main constraint is on structure, whereas the constriction in terms of meaning is looser (this is the reason why many palindromes end up having abstract or even surrealistic meanings). It is probable that, in the current experiment, TL focused mostly on meeting the imperative structural constraints, while placing less emphasis on the meaning of his constructions.

The involvement of the dorsal frontoparietal language circuit interestingly agrees with recent evidence from a neuroimaging study of two experts in "backward speech", which consists in the production of utterances by reversing the order of phonemes (e.g., *mesa – asem*) (Torres-Prioris et al., 2020). Structural MRI analysis in these experts indicated increased grey matter volume, greater integrity of white matter and functional connectivity along dorsal language stream regions mediating phonological encoding and audio-motor integration and supporting short-term storage and manipulation of verbal information. This also converges with structural changes previously observed in simultaneous interpreters (Elmer et al., 2019; Elmer & Kühnis, 2016) and expert phoneticians (Vandermosten, Price, & Golestani, 2016). In this regard, greater activation of the IFG pars triangularis (BA 44) and opercularis (BA 45) during palindrome creation (relative to WM) might be associated with covert manipulation of phonological representations (Fiebach, Schlesewsky, & Friederici, 2002; Gernsbacher & Kaschak, 2003), and greater activation of the SMG with the involvement of phonological short-term memory (Vallar & Papagno, 1995). In addition, the fact that Spanish is a transparent language might have allowed the effective use of strategies based on graphemic in addition to phonemic representations. Consistent with this, palindrome creation (relative to WM and Rest) recruited the superior posterior MTG area bordering the V5/MT region (see 'MTG' in Fig. 2A and B), which has been linked to visual motion attention and perception (Plant, Laxer, Barbaro, Schiffman, & Nakayama, 1993; Schoenfeld et al., 2007; Stevens, McGraw, Ledgeway, & Schluppeck, 2009) and visual motion imagery (Kaas, Weigelt, Roebroeck, Kohler, & Muckli, 2010), and a region in the left fusiform gyrus and neighbouring areas in the ventral occipito-temporal regions known as the visual word form area (VWFA) (Dehaene, Le Clec'H, Poline, Le Bihan, & Cohen, 2002). Thus, TL might have relied on visual imagery as a form of 'inner blackboard' onto which to project letter or word forms to support orthographic sequencing and reordering during palindrome construction.

At the outset of this work, we wondered why humans might be interested in pursuits like palindrome creation, and we framed it as a curiosity-driven activity whereby individuals seek information because it is rewarding by itself. Based on this, we hypothesized that reward-related regions (mid-brain and ventral striatum) might sustain palindrome creation, as in the case of other intrinsically regulated linguistic activities (Ripollés et al., 2016). However, we did not observe an involvement of this subcortical circuitry during palindrome creation in the current task. Although the current study demonstrates that single-case reports can shed light on the brain basis of this singular human activity, it is possible that this null finding is due to a lack of statistical power to detect differences. Besides sample size, there are other factors such as scanner noise, uncomfortableness, or stress (e.g., social pressure) that might have prevented TL from entering a curiosity-driven state and consequently experiencing reward. This might also have been aggravated by the impossibility to write down his ideas inside the scanner, a strategy that is common for palindrome creators, and by the fact that blocks of palindrome creation were alternated with blocks of WM task performance, which might have interrupted his creative process. Future studies might increase the sample size and improve the design to clarify the current null result.

On the other hand, perhaps the most remarkable finding is the involvement of the FPC (BA 10) in difficult (compared to easier) palindrome creation blocks. Of note, this region was also associated with palindrome resolution, as it lighted up in blocks with self-reported successful creation. Crucially, "solved" blocks were mostly easy blocks (6 out of 7). Therefore, it is unlikely that its activation merely reflects operations required to deal with increased difficulty. Rather, we interpret that the increased difficulty allowed to capture more consistently the operations associated with the cognitive effort of creating palindromes. Interestingly, several studies have suggested that the right FPC plays a central role in exploration and information seeking in decision making tasks (Badre, Doll, Long, & Frank, 2012; Daw et al., 2006). A recent study demonstrated a causal link by showing that TMS-induced selective inhibition of the right FPC inhibited information seeking (Wilson, Geana, White, Ludvig, & Cohen, 2014; Zajkowski, Kossut, & Wilson, 2017). In addition, the right FPC (BA 10) is recruited in reasoning tasks that call for monitoring of internally (versus externally) generated information (Christoff & Gabrieli, 2000). For example, previous reasoning studies have reported a strikingly similar activation in the right FPC (BA 10) when participants were solving hard logic problems (compared to easy logic problems, or mathematical problems) (Kroger et al., 2002; Kroger, Nystrom, Cohen, & Johnson-Laird, 2008). Solving these problems involves the construction of models of high relational complexity: one needs to assemble structured representations and reorder them in a way that they relate in a logically valid manner. Similarly, palindromic constructions could be conceived as a complex internal model, in which the order of the composing elements (words or letters) is strongly interdependent, in this case, to meet the constrain on structure. The results are also in alignment with the broader role of the frontopolar cortex in higher cognitive function (Gilbert et al., 2006; Ramnani & Owen, 2004), especially when the tasks request the computation of higher-order relations (Bunge, Helskog, & Wendelken, 2009; Christoff et al., 2001; Koechlin, Basso, Pietrini, Panzer, & Grafman, 1999). In fact, another common aspect between palindrome creation and analogical reasoning is the need to monitor partial results of subgoals or transient internal representations that are needed for inferring higher-order relations (Bunge, Wendelken, Badre, & Wagner, 2005; Christoff, Ream, Geddes, & Gabrieli, 2003). Altogether, the involvement of the right FPC in the current task is consistent with information seeking within an existing internal model (i.e., based on the current palindromic structure), as well as with the need to constantly monitor transient internal representations needed for solving the task.

Lastly, some limitations must be acknowledged and kept in mind when interpreting these findings. First, left-handed individuals, like TL, show variable brain lateralization of language (Pujol, Deus, Losilla, & Capdevila, 1999). Therefore, although we observed large activation of left language-related networks in TL, suggesting that linguistic functions were at least partly left-lateralized, future work is needed to understand the influence of handedness in the current pattern of results. Second, the single-case nature of the study precludes the generalization of the current results to the population of palindromists. In this regard, the findings are meant to provide a starting point that inspires future work employing larger sample sizes. In addition, future studies could also include a control group to explore potential advantages of palindromists in non-linguistic problem-solving tasks. In fact, an interesting idea, perhaps not novel, is borne out from the current findings. Despite it being a linguistic game, palindrome creation seems to implicate processes that are also involved in solving non-linguistic problems, like deductive logic. This commonality might explain the composition of the beforementioned *OuLiPo* group, which has historically joined writers and mathematicians who feel attracted to the creation of palindromes and to other forms of constrained writing. Or think, for example, of the infamous British writer Lewis Carroll, who was also a prominence in formal logics. Fascinatingly, the acquired expertise in activities like palindrome creation might capture an inner drive to exploit rules and relations – and language seems to be a perfect arena for this endeavour.

Author contributions

PLC: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing - Original draft, and Writing - Review & Editing; AG: Conceptualization, Investigation, Writing - Review & editing; DC: Software, Writing - Review & Editing. ARF: Conceptualization, Methodology, Writing original draft, Writing - Review & Editing, Supervision, and Funding acquisition.

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Declaration of competing interests

The authors declare no disclosure of financial interests and potential conflict of interest.

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Appendix A. Supplementary data

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