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Strategic Spatial Anchoring as Cognitive Compensation During Word Categorization in Parkinson's Disease: Evidence from Eye Movements

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Abstract
The association between a word and typical location (e.g., cloud—up) appears to modulate healthy individuals' response times and visual attention. This study examined whether similar effects can be observed in a clinical population characterized by difficulties in both spatial representation and lexical processing. In an eye-tracking experiment, participants categorized spoken words as either up-associated or down-associated. Parkinson's disease patients exhibited a tendency to maintain their visual attention in the upper half of the screen, however, this tendency was significantly lower when participants categorized concepts as down-associated. Instead, the control group showed no preference for either the upper or lower half of the screen. We argue that Parkinson's disease patients present an over-reliance on space during word categorization as a form of cognitive compensation. Such compensation reveals that this clinical population may use spatial anchoring when categorizing words with a spatial association, even in the absence of explicit spatial cues.

Keywords Parkinson's disease · Word categorization · Spatial representation · Eye tracking · Blank-screen paradigm

Introduction

Parkinson's disease (PD) is a neurodegenerative disorder that affects 1% of the global population over 60 years of age. Existing clinical and experimental evidence shows that, compared to neurologically healthy peers, people with PD present significantly diminished performance in perception, memory, language and executive functions (García et al. 2016; Murray 2008; Troster 2011). Consequently, patients may also present impaired processing of spatial information such as distance relations and movement

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through confined spaces (Almeida and Lebold 2010; Lee and Harris 1999). Regarding language, existing evidence suggests that PD impairs both comprehension and production at the lexical level (Cardona et al. 2013; Ibáñez et al. 2013; Monetta and Pell 2007). For the most part, research has identified effects at later stages of linguistic processing thought to be linked to strategic aspects of comprehension rather than to automatic processing, early activation or lexical access (Friederici et al. 2003; Angwin et al. 2006; Copland 2003). Consequently, patients with PD are characterized by a particularly interesting profile with concomitant deficits in lexical and spatial processing.

In turn, existing literature in healthy adults shows that the association between words and spatial representation has behavioral effects that are observable in button-pressing response latencies and in visual attention-related measures such as saccadic eye movement (Bergen et al. 2007; Dudschig et al. 2013; Lachmair et al. 2011; Pecher et al. 2010). In general, these effects depend on the congruency between the lexical items and spatial locations. For instance, the word "cosmos" is strongly associated with an upper location in space, while the word "miner" is strongly associated with a lower location in space (see Table 2). Thus, a task-response that demands an upward movement produces shorter reaction times for words such as "cosmos" (relative to "miner), and vice versa for a downward movement response (e.g. Lachmair et al. 2011). What remains unclear is how such congruency effects may be instantiated in a clinical population, such as PD patients, characterized by difficulties in both spatial representation and lexical processing relative to a control population.

Using a blank screen paradigm (see Spivey and Geng 2001), we monitored participants' eye movements as they categorized a set of spoken words as either up-associated or down-associated objects. A first possible scenario is that both the clinical and control groups show an interaction between word meaning and the typical location of objects to which the words refer, reflected in a gaze pattern towards the spatial region that corresponds to the word meaning association (i.e., upper vs. lower screen sections). This would indicate that PD patients have normal access to spatial representations during lexical processing. In an alternative scenario, only the control group shows such interaction, suggesting that the lexical processing of this class of words is affected in the PD group. In a third and most likely scenario, the control group exhibits no effects of word-location association, while the effect is observed in the PD group. Indeed, previous research suggests that difficulties in language processing appear to be mediated by a compensatory mechanism that demands additional cognitive effort (Friederici et al. 2003; Longworth et al. 2005). For instance, functional neuroimaging (Grossman et al. 2003) that compared syntactic processing between participants with PD and healthy controls revealed the presence of compensatory mechanisms in the former, evidenced by upward compensatory activity in cortical functioning. The results suggest that this upward compensatory activity allows PD patients to maintain precision in sentence comprehension.

A similar observation has been made in cognitively healthy older adults in terms of increased activity in regions that do not usually participate in syntactic processing. This has been interpreted as the way in which the brain compensates for the diminution of its capacities as a result of aging (Peelle et al. 2010). Based on these and other results (Wingfield and Grossman 2006), it has been proposed that older individuals distribute cognitive resources differently in order to cope with language processing cognitive demands (Stine-Morrow et al. 2006). This is interesting when considering that, from a neurological perspective, aging can produce conditions similar to early-stage PD (Collier et al. 2017). Consequently, identification of an effect in the PD group only would suggest that in a blank screen paradigm, word-location association modulates visual attention only in populations that present a compensatory mechanism for lexical categorization tasks.

Evidence from research into movement control is consistent with the idea of compensatory mechanisms presented by PD patients. Almeida and Lebold (2010) conducted a study examining the effect of spatial processing and displacement in participants with PD. The authors compared a PD group confirmed to be experiencing freezing of gait, a PD group without freezing of gait, and a healthy age control group. Participants were required to walk through doors of differing diameters (narrow/normal/wide) while spatio-temporal aspects of their gaits and perception were evaluated. Results showed that for both PD groups, perception of walking distance and walking time was affected as the door was narrowed. The authors argue that, as a means of compensation, PD patients display greater perceptual effort compared to healthy controls. This perceptual effort regulates and compensates for their motor deficit, affording them greater stability and control of their displacement through "more careful" steps.

An understanding of the way in which compensatory mechanisms are exhibited by PD patients during language comprehension may have important implications for clinical practice. On one hand, the examination of compensatory mechanisms in a controlled experimental task can help to identify those linguistic processes that require greater effort on the part of people with PD. In turn, the identification of such processes is crucial to the design of therapy, particularly for cognitive and linguistic rehabilitation. On the other hand, the behavioral nature of compensatory mechanisms exposes the way in which the impaired cognitive systems of PD patients are already coping with tasks that are highly demanding in terms of cognitive resources. This information may point to ways in which therapy can be implemented to utilize and potentially enhance pre-existing compensation mechanisms. More concretely, it is possible that a cognitive-linguistic intervention program that incorporates lexical-spatial tasks as part of its routines might be effective in palliating some of the symptoms related to the illness.

The present study seeks to examine the link between lexical and spatial processing in PD patients by comparing how spatial representations associated with the typical locations of objects (e.g., cloud—up) modulate visual attention in PD patients and in neurologically healthy control pairs during a lexical categorization task.

The Experiment

Methods

Participants

A sample of 36 participants were recruited, who took part of the experiment voluntarily. Half of them were PD patients (mean age = 71.23; age range = 59–84) while the other half were healthy control adults (mean age = 70.28; age range = 55–83) matched by age and level of formal education with the clinical sample. Prior to participation, all participants read and signed an informed consent which was approved by the Comité de Ética, Bioética y Bioseguridad de la Vicerrectoría de Investigación y Desarrollo, Universidad de Concepción (Project 1150336). The inclusion criteria were as following: to have normal or corrected-to-normal vision and audition; to be monolingual of Spanish; to have at least primary school level of education; to reach at least 65% of accuracy in the word categorization

Table 1 Scores for the 16 PD patients in the Neuropsychological Assessment based on the Mini-Mental State Examination (MMSE), the Barthel Index for Activities of Daily Living (ADL), and the Unified Parkinson's Rating Scale (sub-scales and total score)

ID	MMSE	Barthel	UPDRS I	UPDRS II	UPDRS III	UPDRS IV	Total UPDRS
1	19	Normal	0	15	28	4	47
2	19	Normal	0	14	25	3	42
3	19	Normal	0	15	16	4	35
4	15	Normal	2	13	15	5	35
5	18	Normal	0	16	17	5	38
6	13	Normal	4	28	17	2	51
7	17	Normal	2	16	20	2	40
8	19	Normal	0	15	21	3	39
9	13	Low	4	30	39	5	78
10	19	Normal	0	15	20	3	38
11	18	Low	2	27	38	6	73
12	19	Normal	0	16	15	2	33
13	18	Normal	0	15	19	3	37
14	19	Normal	0	14	21	4	39
15	18	Normal	3	16	24	2	45
16	19	Low	0	28	37	4	69

ID: Participants identification number; MMSE: Mini Mental State Evaluation; Barthel: *Index* for *Activities of Daily Living* (ADL); UPDRS I: Mentation, Behavior and Mood; UPDRS II: Activities of Daily Living; UPDRS III: Motor Examination; UPDRS IV: Complications of Therapy

task; to have a normal cognitive state; and for the PD group, to have a mild to moderate diseases' level. Our initial sample included 18 PD patients, but one was excluded from the final sample due to a technical error in the presentation of the stimuli during the experiment, while another was excluded due to low response accuracy (< 65%). Table 1 presents the results of a neuropsychological assessment in our final PD sample.

Participants were initially contacted through a link between the University and a local association of Parkinson's disease patients. We coordinated meetings with the association authorities and offered general audience talks for potential participants in order to explain the objectives of the study. People with PD who were willing to collaborate received a cognitive evaluation using the Mini Mental State Evaluation (MMSE). Subsequently, participants were referred to the Psycholinguistic Laboratory at the University of Concepción. They were reminded to continue the regular use of their medication (typically, a commercial form of L-DOPA, which is a precursor to dopamine), which they confirmed to have taken early in the morning (around 8:00 a.m.), approximately four hours before arriving at the Lab.

Materials and design

We selected 60 Spanish words based on the results of a pre-test conducted on an independent sample of participants. This norming process evaluated the strength of the spatial association (i.e., "up" or "down") of a larger set of words. For example, the word '*Jupiter*' was highly associated the "up" location. In turn, the word '*well*' was strongly associated with the "down"

Table 2 List of the words (translated into English) and their mean rating scores

"Up" words	Mean score	"Down" words	Mean score
Jupiter	8.88	Orchard	3.32
Cosmos	8.71	Crypt	3.28
Orbit	8.34	Pantheon	3.25
Thunderlight	7.76	Boot	3.16
Condor	7.43	Lagoon	3.07
Hawk	7.22	Grass	2.97
Volcano	6.68	Ankle	2.93
Hill	6.63	Shoe	2.92
Vulture	6.49	Mushroom	2.78
Oriel	6.32	Sole	2.66
Cascade	6.15	Tunnel	2.59
Lighthouse	6.09	Worm	2.34
Crater	6.03	Copper	2.16
Cornice	5.84	Anchor	1.93
Missile	5.68	Mine	1.75
Neptune	8.83	Meadow	3.35
Star	8.67	Pedal	3.29
Cloud	8.05	Lake	3.25
Thunder	7.66	Socket	3.22
Goddess	7.31	Puddle	3.07
Giant	7.07	Grazing	3.00
Hurricane	6.64	Crack	2.95
Dragon	6.50	Hole	2.92
Tower	6.39	Den	2.85
Castle	6.17	Duck	2.68
Globe	6.10	Diver	2.65
Nest	6.08	Cave	2.51
Crest	5.87	Pit	2.29
Branch	5.84	Miner	2.05
Oak	5.68	Well	1.81

Participants responded on a scale of 1 to 9, where 1 was strongly associated with "down" and 9 was strongly associated with "up"

location. Table 2 shows the final set of critical words used in the experiment, along with their mean rating scores on a scale from 1 (strongly associated with "down") to 9 (strongly associated with "up"). Another 60 words that did not have strong spatial associations served as fillers. Aural stimuli were recorded by a male Spanish native speaker in a sound-proofed room. Spoken words were presented without any linguistic context, and the mean word duration was 733.53 ms (range: 500–966 ms).

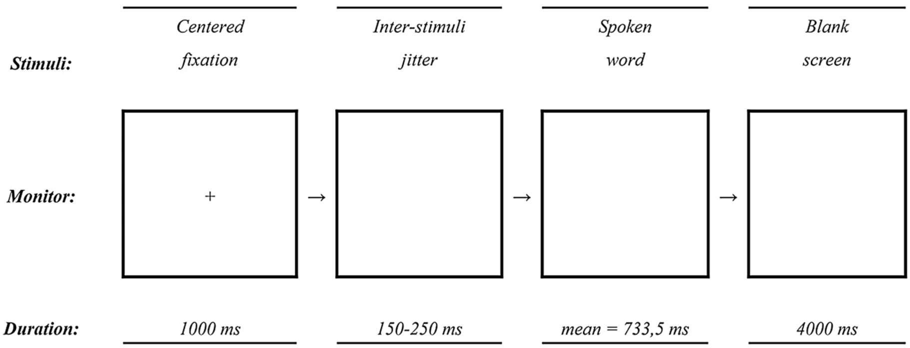

Fig. 1 Experimental trial example. Participants saw a fixation dot for one second before hearing the critical word, and responded verbally whether the concept was up- or down-associated

Equipment

We used an SMI RED500 system (SensoMotoric Instruments), which is a binocular high-speed screen-based eye tracker with a sampling frequency of 500 Hz. The tracker uses infrared LEDs to illuminate participants' eyes, and has a spatial accuracy of 0.4°.

Procedure

We asked participants to listen to words with strong vertical associations (up and down) while looking at a blank screen. They were instructed to verbally categorize these words as either up-associated or down-associated. Throughout the experiment, participants' eye movements were recorded using the eye tracking system above-described. The eye tracker delivers a data point consisting in an x- and a y-coordinate values (i.e., gaze location) every 2 ms. This enabled us to examine whether potential effects of word-location association could appear online as participants process spoken words, or whether these effects emerge following lexical access and during categorization.

The data collection session began at noon, meaning that participants took part in the experiment in an "off" state. On the day of the evaluation, participants' hearing capabilities were assessed using an audiometry test. Once severe hearing problems had been ruled out, participants read and signed an informed consent before taking part in the experiment. Before the experiment began, each participant was seated comfortably at a distance of 90–100 cm from the computer screen, and a five-point calibration procedure was conducted. Recalibration was carried out after every 10 trials. During the experiment, participants listened to the spoken words and categorized them verbally, while their eye movements were recorded using an SMI RED500 tracking system. Each trial began with a fixation cross followed by jitter—that is, a random time interval between 150 and 250 ms—before a single spoken word was heard. This jitter was used to prevent the anticipation of the onset of the spoken word after the cross was removed. Participants were instructed to decide whether the word had an "up" or "down" association (see Table 2), and to respond accordingly by uttering either "*up*" or "*down*". They had 4000 ms to give their response before the next trial began. Figure 1 shows the order of events of each trial.

Data Analysis

Response accuracy to critical items was calculated to ensure that participants were paying attention to the task. Accuracy was relatively high among participants, with the exception of one who responded correctly to fewer than 65% of trials and was consequently excluded from the sample. For the remaining participants, all trials with incorrect responses were removed prior to analysis.

Using the SMI BeGaze 3.5 software we created two areas of interest based on the center of the y-axis of the computer screen. This resulted in an upper region and a lower region of interest. We then obtained a fixation duration report containing the order of fixations and their durations. The report also included the fixation location on the x- and y-axes, which in turn enabled us to determine whether the fixation occurred in the upper or lower region of the screen. The fixation report was extended using the R Project for Statistical Computing software (R Core Team 2020), with which we inspected every millisecond per participant, per trial and per area of interest. A value of 1 was given to the area of interest upon which participants were fixating at each given time step, resulting in a trial-based fixation report. Arguably, the time needed for saccade planning is around 200 ms (Fischer and Ramsperger 1984). In turn, the response time of participants in our experiment was around 1000 ms. Thus, we created two time-windows of 800 ms each for analysis: an early time window (200 ms to 1000 ms after word onset) and a late time window (1000 ms to 1800 ms after word onset). This was achieved by aggregating the data by participant and item, and across time steps within a given time window.

Inferential analysis was conducted in R (R Core Team 2020) using two generalized linear mixed-effects regressions (Bates et al. 2015): one for the PD group and one for the control group.[1] Generalized Linear Mixed Models (GLMM) provide multilevel analysis capable of including cross random effects for participants and items in a single regression, and simultaneously accommodate the variation of participants and items around the independent variables. It is an alternative to a separated analysis of variance by items and by participants (i.e., F1, F2), and represents a powerful statistical tool in the context of psycholinguistic research. This is particularly true where different linguistic instantiation of the same experimental condition (i.e., items) is known to add variation to that of the experimental manipulation (Clark 1973). We opted for a fully specified model approach; that is, the inclusion of maximal random structure justified by the design (Barr et al. 2013).

Our regressions included the aggregated proportion of fixation as the dependent variable, and the region of interest (i.e., upper region, lower region), the type of association that the word carried (i.e., "up", "down") and the time window (i.e., early, late) as predictors. The region of interest and the word type were centered using a zero-sum contrast (or contrast coding) which compares predictor level means to one another. To observe the changes in time, we used a sliding contrast (Venables and Ripley 2002) in the time window factor, which set the early time window as a reference group. Regressions included the main effects of all predictors and the interaction effects between them. The random structure of the regressions included random intercepts for participants and items, and random slopes of the main effects of interest region, word association and time window—along with their interaction—for the random intercepts of both participants and items. GLMM outputs produce estimates, standard errors of the mean, and z-values and p-values. To

[1] In "Appendix", we present a regression model that directly compares experimental conditions, time windows and groups. The results point to the same conclusions.

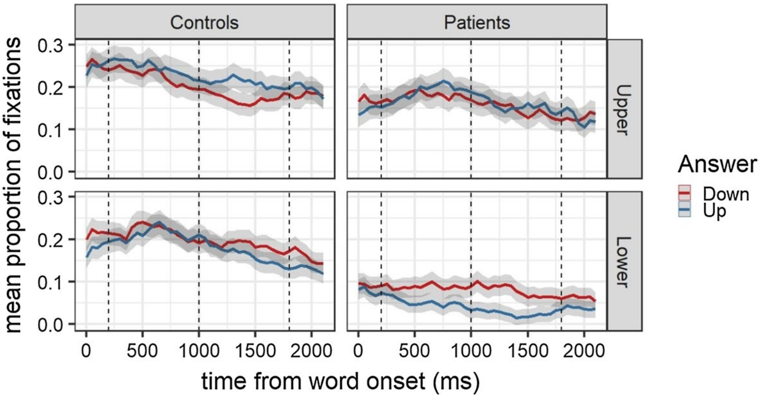

Fig. 2 Mean fixation proportion as a function of region of interest, word condition and group. Fixation proportion means were aggregated in time steps of 50 ms. Word association conditions are represented by the different line colors. Ribbon widths represent within-subject adjusted 95% confidence levels, calculated by participant. Vertical dashed lines represent the limits of the two critical time windows

facilitate convergence, we changed the glmer function default optimizer to “nloptwrap” and removed the random correlations from the model, keeping the within-unit intercepts (Barr et al. 2013). All our data and code are available at https://osf.io/gyqmf/.

Results

Figure 2 shows the average proportion of fixations on the upper and lower regions of the screen for the two word-conditions and participant groups during the first 2000 ms after word onset. For the control group, the graph shows no clear differences between the different experimental conditions. Only in the second part of the late critical time window is there a congruency effect. From around 1250 ms after word onset we see an increase in fixations on the upper region when participants responded *up*, and a decrease in fixations on that region when participants responded *down*. However, this trend is short-lived, and disappears 200 ms later. For the PD group, Fig. 2 shows an overall preference for the upper region of the screen, independent of word condition. This effect appears across both the early (200 to 1000 ms) and late (1000 to 1800 ms) time windows. In addition, the plot shows that participants’ fixations on the upper region of the screen were not modulated by the vertical association of the word they heard (or by the response they gave). However, participants’ fixations on the lower region of the screen were modulated by the word condition. A higher proportion of fixations on this area was observed when participants heard a word with a “down” association, in particular after the average response time ($\approx$1000 ms after word onset), when participants vocally responded *down*.

The pattern of results was confirmed by the results of the GLMM analyses (Table 3). The first of these regressions (control group) revealed a time window effect only ($\beta = -0.774$, $se = 0.121$, $z = -6.40$, $p < 0.001$), reflecting an overall decrease in fixation proportions in the second time window. No other reliable effects were observed, suggesting that the gaze pattern of healthy older adults is not modulated by the vertical association of words, or by producing the words “up” or “down” as a response to that association. By contrast, the results of the second regression (PD group) revealed main effects of word ($\beta = -0.295$,

Table 3 Main and interaction effects in the generalized linear mixed-effects regression models on fixation proportions for both the PD patients and control group

	β	*se*	*z*	*p*
Control group results				
(Intercept)	−4.772	1.200	−3.98	0.000***
Word	0.045	0.050	0.90	0.367
Region	0.204	0.189	1.08	0.281
Time window contrast	−0.774	0.121	−6.40	0.000***
Word * region	0.116	0.069	1.69	0.092
Word * time window contrast	0.006	0.093	0.06	0.950
Region * time window contrast	0.010	0.094	0.10	0.918
Word * region * time window contrast	0.075	0.092	0.81	0.418
	β	*se*	*z*	*p*
PD patients results				
(Intercept)	−5.754	1.114	−5.17	0.000***
Word	−0.295	0.136	−2.17	0.030*
Region	1.153	0.410	2.81	0.005**
Time window contrast	1.033	0.443	2.33	0.020*
Word * region	0.315	0.117	2.69	0.007**
Word * time window contrast	−0.161	0.150	−1.07	0.284
Region * time window contrast	−0.171	0.178	−0.96	0.338
Word * region * time window contrast	0.183	0.158	1.16	0.246

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

$se=0.136$, $z=-2.17$, $p<0.05$), region ($\beta=1.153$, $se=0.410$, $z=2.81$, $p<0.01$), and time window ($\beta=1.033$, $se=0.443$, $z=2.33$, $p<0.05$). The main effect of region reflects the evident preference for the upper region (see Fig. 2), while the main effect of word is likely to reflect the gaze differences observed in the lower region, depending on word condition and response. By contrast, the time window effect appears to be driven by the overall decrease in the second time window (relative to the first time-window) in the upper region. More importantly, the regression model also revealed a reliable interaction effect between word and region ($\beta=0.315$, $se=0.117$, $z=2.69$, $p<0.01$). This interaction effect reflects the distinct effects of word type on the gaze pattern towards the regions of interest. While the upper region was preferred overall, this trend decreased significantly when participants heard a down-associated word and responded with *down* (see Fig. 2).

Discussion

The present study was aimed to compare how the relation between spatial representations and objects' location modulated visual attention in Parkinson's disease (PD) patients relative to healthy control pairs during word processing and categorization. Results from the PD experimental group showed that, overall, participants' visual attention was focused on the upper half of the screen, regardless of whether they heard a word that was up-associated or down-associated. However, when categorizing a down-associated word, this overall trend decreased, with participants tending less to direct their gaze to the upper region of the screen. These gaze patterns were captured by the linear mixed regression analysis, which showed a reliable main effect of location and an interaction effect between word type (up- or down-associated) and screen region (upper vs. lower). By contrast, no such effects were observed in the control group.

Assuming that word-location associations are capable of modulating visual attention in healthy adults (Dudschig et al. 2013; Ostarek et al. 2018), the lack of such an effect in the control group may be related to at least two aspects of the experiment. First, our experimental paradigm did not require participants to direct their visual attention to any particular spatial location (cf., e.g., Ostarek et al. 2018), since we used a blank screen paradigm (see Spivey and Geng 2001). This is different from previous studies which prompted spatial locations using different visual cues (Bergen et al. 2007; Dudschig et al. 2013; Lachmair et al. 2011; Pecher et al. 2010; Ostarek et al. 2018; Richardson et al. 2001). Arguably, visual cues may facilitate the link between semantic and spatial representations, enabling such associations to permeate a behavioral response. Second, we presented participants with single spoken words for categorization, with no additional contextual support. Again, previous studies have found a more robust effect of sentences that imply movement or locations compared to the effects of isolated single words (see Bergen et al. 2007). Consequently, the connection between the observed behavior (i.e., eye gaze in this case) and the task is rather subtle in our study. It is possible, therefore, that healthy adults who present no difficulties in later stages of semantic processing do in fact activate word-location association, but that no observable eye movement behavior related to those associations is found.

By contrast, when participants with PD are confronted with diminished contextual information (i.e., single words, blank screen) and a semantic categorization task—which is related to late semantic processes and strategic categorization, known to be altered in PD patients (Angwin et al. 2006; Copland 2003; Cardona et al. 2013)—it is possible that they cope with these demands through a cognitive compensation strategy. In fact, existing evidence suggests that older adults rely more on contextual information than younger adults do (Wingfield et al. 1991). Moreover, cognitive compensation has been described as the strategic use of contextual information to aid linguistic/cognitive processing (Wingfield and Grossman 2006). Confronted with a task that may be highly demanding for PD patients, it seems plausible that they would attempt to use any sort of information available to compensate for their deficit. Thus, looking down when uttering the word "down" suggests that eye movement could be acting as a support or anchor during lexical categorization of words associated with a spatial representation. This phenomenon can be compared to the study by Almeida and Lebold (2010) in which the altered spatial representation was reflected in a more careful walking pattern. Thus, we believe that people with PD use strategic self-regulatory mechanisms that involve greater perceptual effort, and that these mechanisms facilitate the anchoring, location, tracking and organization of spatial information; a phenomenon known as spatial indexing (Richardson and Kirkham 2004). Existing research has shown that subjects with PD maintain automatic lexical recognition relatively intact, but present difficulties in the tasks involving categorization (Copland 2003), selection of alternatives, and inhibition of accessory information (Longworth et al. 2005). The time course of the eye movement patterns in the PD group reveals that the effects of word-location association occur exactly as participants prepare to provide the response, and not during spoken word comprehension. This late influence of spatial association is likely to be part of strategic processing.

Finally, our results might have the potential to support clinical practices by informing innovative cognitive-linguistic training and rehabilitation for PD patients. Many existing cognitive training programs only superficially address aspects of a lexical-spatial nature and focus on working memory skills, executive functions, processing speed, and isolated visuospatial skills (Leung et al. 2015). We suggest that cognitive training could exploit this compensatory spatial anchoring for the benefit of improved management and control over these everyday domains.

Conclusion

The results of the present study contribute to our understanding of the psycholinguistic manifestations of Parkinson's disease (PD). The patterns of ocular movement reflected a differentiation in the condition of this clinical population compared with healthy counterparts (Wong et al. 2018). Two important limitations of our study must be noted, however. First, as is often the case with research on special populations, our sample size is relatively small. That said, we sought to compensate for this by requiring participants to respond to a relatively large number of items (n = 60). Thus, while our sample size is small, the total number of observations per condition is acceptable. The second limitation is that our main conclusions are derived from behavioral data alone and not from a physiological or neuroanatomical data. We believe that the present research should be taken as initial evidence for a spatial anchoring compensatory mechanism in PD patients. Future research could explore the neuroanatomical basis or the physiological correlates of this mechanism, which could in turn further our understanding of the ways in which PD patients cope with their cognitive and linguistic difficulties.

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Compliance with Ethical Standards

Conflicts of interest The authors declare that the research was conducted in the absence of any scientific, commercial or financial relationships that could be construed as a potential conflict of interest.

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and national research committee and with the Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all individual participants included in the study.

Appendix

We present the results from a GLMM analysis that directly contrast the experimental groups. We followed a model comparison approach given the highly complex random structure this analysis demands if all random factors justified by the design are included. We compared four models of increasingly complex random structure: (1) a random intercept model only, (2) a main effect random slopes model, (3) a model with all two-way interactions as random slopes, and (4) a model with all three-way interactions as random slopes. Model comparison revealed that the most parsimonious model was that with main effects as random slopes. All our data and code are available at https://osf.io/gyqmf/.

	β	*se*	*z*	*p*
(Intercept)	−5.210	0.844	−6.17	0.000***
Word	−0.097	0.065	−1.50	0.135
Region	0.590	0.196	3.01	0.003**
Time window contrast	−0.237	0.101	−2.35	0.019*
Group	0.409	0.844	0.48	0.628
Word * region	0.182	0.041	4.47	0.000***
Word * time window contrast	−0.059	0.078	−0.75	0.451
Word * group	0.153	0.065	2.35	0.019*
Region * time window contrast	0.012	0.078	0.16	0.877
Region * group	−0.391	0.196	−2.00	0.045**
Time window contrast * Group	−0.011	0.101	−0.11	0.915
Word * region * time window contrast	0.102	0.078	1.31	0.192
Word * region * group	−0.096	0.041	−2.36	0.018*
Word * time window contrast * group	0.081	0.078	1.03	0.304
Region * time window contrast * group	−0.027	0.078	−0.35	0.728
Word * region * time window contrast * group	−0.035	0.078	−0.45	0.652

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