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RESEARCH ARTICLE

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Differential contribution of language and executive functioning to verbal fluency performance in glioma patients

Ellen Collée[1] | Esther van den Berg[2] | Evy Visch-Brink[1] | Arnaud Vincent[1] | Clemens Dirven[1] | Djaina Satoer[1]

[1]Department of Neurosurgery, Erasmus MC – University Medical Centre, Rotterdam, The Netherlands

[2]Department of Neurology and Alzheimer Center Erasmus MC, Erasmus MC – University Medical Center, Rotterdam, The Netherlands

Correspondence
Ellen Collée, Doctor Molewaterplein 40, 3015 GD Rotterdam, The Netherlands.
Email: k.collee@erasmusmc.nl

Abstract

Glioma patients often suffer from deficits in language and executive functioning. Performance in verbal fluency (generating words within one minute according to a semantic category–category fluency, or given letter–letter fluency) is typically impaired in this patient group. While both language and executive functioning play a role in verbal fluency, the relative contribution of both domains remains unclear. We aim to retrospectively investigate glioma patients' performance on verbal and nonverbal fluency and to explore the influence of language and executive functioning on verbal fluency. Sixty-nine adults with gliomas in eloquent areas underwent a neuropsychological test battery (verbal fluency, nonverbal fluency, language, and executive functioning tests) before surgery (T1) and a subgroup of 31 patients also at three (T2) and twelve months (T3) after surgery. Preoperatively, patients were impaired in all verbal fluency tasks and dissociations were found based on tumour location. In contrast, nonverbal fluency was intact. Different language and executive functioning tests predicted performance on category fluency animals and letter fluency, while no significant predictors for category fluency professions were found. The longitudinal results indicated that category fluency professions deteriorated after surgery (T1–T2, T1–T3) and that nonverbal fluency improved after surgery (T1–T3, T2–T3). Verbal fluency performance can provide information on different possible underlying deficits in language and executive functioning in glioma patients, depending on verbal fluency task selection. Efficient

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task (order) selection can be based on complexity. Category fluency professions can be selected to detect more permanent long-term deficits.

KEYWORDS
executive functioning, glioma, language, nonverbal fluency, verbal fluency

INTRODUCTION

Glioma patients and verbal fluency

Gliomas are primary brain tumours that are often located in eloquent areas of the brain (Duffau, 2005). The current preferred treatment to optimize safe tumour resection is awake surgery with direct electrical stimulation (Duffau, 2008). Before surgery, glioma patients often suffer from (mild) cognitive deficits, which may depend on different factors such as tumour volume and location (Van Kessel et al., 2019). Deficits can occur in language, such as word retrieval difficulty (Racine et al., 2015), and in executive functioning, such as difficulties with divided attention (Satoer et al., 2012) and mental flexibility (Miotto et al., 2011). After surgery, a decline or new deficits in language and executive functioning frequently occur, often followed by spontaneous recovery within three months in case of language deficits (Duffau et al., 2002; Finch & Copland, 2014; Van Kessel et al., 2020). However, language deficits can also persist in the long-term, for example in spontaneous speech (Satoer et al., 2018).

It is crucial to detect these deficits, which can be done by using standardized tests. As testing time is often limited in clinical practice, it is of utmost importance to compile a compact battery of sensitive tests in at least the domains of language and executive functions for glioma patients. A sensitive and quick test that is widely used in both clinical care and research is verbal fluency. The clinical relevance of this efficient test is underlined by the fact that verbal fluency performance is also related to quality of life (Nakajima et al., 2022). In verbal fluency, participants are asked to generate as many unique words as possible within a given semantic category such as animals and professions (semantic or category fluency) or starting with a given letter (phonemic or letter fluency) within a limited time span. Impairments in verbal fluency in glioma patients have been reported (Papagno et al., 2012). Glioma patients showed impairments preoperatively and postoperatively (three months and one year after surgery) in category and letter fluency, whereas category fluency even significantly declined at three months after surgery compared to preoperative performance (Satoer et al., 2014). In contrast, letter fluency significantly improved between three months and one year after surgery.

Demographics, such as age, and tumour-related factors, such as histology and location, can influence verbal fluency performance in glioma patients (Pranckeviciene et al., 2020; Talacchi et al., 2011). Left-hemispheric glioma patients performed worse on category fluency than right-hemispheric glioma patients, emphasizing that the left hemisphere is mainly involved in the task (Biesbroek et al., 2021; Goldstein et al., 2004). In particular, patients with left temporal gliomas showed deficits in category fluency, while patients with left frontal gliomas showed deficits in letter fluency (Zigiotto et al., 2022).

Cognitive processes in verbal fluency

In healthy participants, various cognitive processes underlie verbal fluency performance. Examples of involved language-related processes are lexical knowledge (Ruff et al., 1997) and lexical retrieval (Kraan et al., 2013). Executive functions also come into play, for example when semantic and/or phonological constraints must be followed. A reported, yet sometimes debated, executive process involved in verbal

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fluency is working memory (Fisk & Sharp, 2004; Unsworth et al., 2011). Recently, cognitive flexibility and inhibition were indicated as important executive processes in verbal fluency in healthy participants, in combination with more general functions such as processing speed and attention (Amunts et al., 2020).

According to Azuma et al. (1997), category fluency relies on hierarchical semantic memory organization, meaning that semantic categories have subgroups on which organized lexical searches can be based. For example, when naming animals, one can focus on subgroups such as pets or zoo animals. However, lexical searches for letter fluency items are driven by phonological processes and not by semantic subcategories and may therefore rely more on executive functioning processes such as advanced organizational, strategic, and response inhibition abilities (Riva et al., 2000; Strauss et al., 2006), and clustering and switching (Troyer et al., 1998). When focusing on the specific words produced during verbal fluency, clustering is when words from the same semantic or phonemic subcategory are grouped. Switching is when a switch is made to a new subcategory.

Although it has been suggested that category fluency may rely more on verbal ability and letter fluency on executive functioning (Shao et al., 2014), the specific relative contribution of language and executive functioning in verbal fluency performance remains unclear. Aita et al. (2018) and Patt et al. (2017) reported that verbal fluency performance in healthy participants ($M = 19.8$ and $M = 47.2$ years old, respectively) was associated with both language (phonological decoding, semantic knowledge) and executive functioning (working memory, fluid reasoning, shifting/updating), with stronger effects for category fluency compared to letter fluency (Aita et al., 2018). In contrast, another study reported that both category and letter fluency in healthy older adults ($M = 71.8$ years) were only predicted by executive functioning (updating ability, Shao et al., 2014). These discrepancies may be caused by the inclusion of different participant groups (younger vs. older adults) and the use of different language and executive functioning tests to assess predictors for verbal fluency across studies.

Literature on the relative contribution of language and executive functioning in verbal fluency in neurological patient groups is scarce, and results are also mixed. For example, while some results indicate that language and not executive functioning predicted category and letter fluency performance in patients with multiple sclerosis (Lebkuecher et al., 2021) and in a group of patients with various neurological disorders (e.g. stroke, dementia, neoplasm, and multiple sclerosis, Whiteside et al., 2016), others found that both language and executive functioning predicted scores on category and letter fluency in patients with multiple sclerosis (Delgado-Álvarez et al., 2021). The relative contribution of language and executive functioning in verbal fluency in glioma patients has not been investigated so far and may differ from other neurological patient groups.

Nonverbal fluency

Nonverbal fluency tasks are nonverbal analogues of verbal fluency tasks and measure executive functioning only (Regard et al., 1982), such as The Five-Point Test (FPT; Regard et al., 1982). In the FPT, as many unique figures in a given configuration of five dots must be generated within three minutes (see Figure 1). The FPT became the first nonverbal fluency task that was reliable and valid (Lezak, 1995; Spreen & Strauss, 1998) after it resolved the limitations of the previously published Design Fluency Test (Jones-Gotman & Milner, 1977). The FPT measures various executive processes such as cognitive flexibility, strategy implementation, and rule-breaking in healthy adults (Goebel et al., 2009).

Only a few studies investigated nonverbal fluency in glioma patients, and for both right and left-hemispheric glioma patients, some studies show mild nonverbal fluency impairments (Archibald et al., 1994; Marin et al., 2017; Racine et al., 2015), while others do not (Archibald et al., 1994; Satoer et al., 2017). Nonverbal fluency is reported to rely on frontal regions of both hemispheres (Baldo et al., 2001). Comparing nonverbal fluency performance to verbal fluency performance may help

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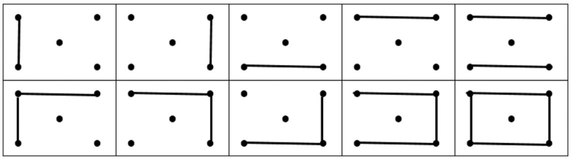

FIGURE 1 Example of the Five Point Test (based on Rinaldi et al., 2013).

disentangle the relative contribution of language and executive functioning in verbal fluency performance in glioma patients.

The present study

The first aim of the present study was to investigate the verbal and nonverbal fluency performance of glioma patients before surgery compared to the healthy population and investigate the influence of tumour location (lobe and hemisphere) on verbal and nonverbal fluency performance before surgery. We hypothesize that performance on all verbal fluency tasks will be impaired preoperatively, especially in patients with tumours in the left hemisphere. Additionally, we expect that letter fluency performance will be impaired in patients with frontal tumours, while category fluency performance will be impaired in non-frontal tumours. The second aim was explorative and was to investigate the influence of language, executive functioning, and demographic/clinical factors on verbal fluency performance in glioma patients before surgery.

The following aims have a longitudinal approach. The third aim was to investigate the short and long-term effects (3 months and 1 year after surgery) of surgery on verbal and nonverbal fluency performance in glioma patients. In line with Satoer et al. (2014), we hypothesize that category fluency will decline after surgery in the short-term, but remain stable in the long-term, and that letter fluency will improve in the long term. The fourth aim was to investigate the influence of hemispheric tumour location on verbal and nonverbal fluency performance in glioma patients over time. We expect lower verbal fluency scores in patients with left-hemispheric tumours than right-hemispheric tumours at all time points, but we do not expect performance differences in nonverbal fluency based on hemispheric tumour location.

The results of this study may provide more insight into which domains (language/executive functioning) and specific processes are needed in the different verbal fluency tasks. This information can then be used in the clinic, after administrating these quick verbal fluency tests, to get a better understanding of language and executive functioning deficits in individual glioma patients with implications for further diagnostics and rehabilitation.

METHODS

Subjects

The current retrospective study assessed the cognitive functioning of 69 native adult Dutch-speaking patients diagnosed with a suspected low-grade glioma in eloquent areas who underwent awake craniotomy between 2004 and 2013 at the following Dutch hospitals: Erasmuc MC - University Medical Center (Rotterdam), Haaglanden Medisch Centrum (Den Haag) or Elisabeth-TweeSteden Hospital (Tilburg). All patients underwent a comprehensive neuropsychological test protocol preoperatively, and a subgroup ($n = 31$) also postoperatively. The pathological WHO grade of the tumour was determined postoperatively by a neuropathologist from tissue obtained during tumour resection. Tumour location

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was determined by a neuroradiologist using 3D T1-weighted MRI and 2D T2-weighted MRI studies. Demographic and clinical data of the patients are shown in Table 1. The medical ethical committee of Erasmus MC - University Medical Center approved this study and waived the need for written informed consent considering that this is a retrospective study. A healthy Dutch control group (*N* = 27; age: *M* = 43.2, *SD* = 21.7; education on Verhage scale: *M* = 5.5, *SD* = 1.1, see footnote of Table 1 for scale information) was recruited in personal environments (e.g. friends, family members) for the interpretation of patients' nonverbal fluency test scores.

TABLE 1 Demographic and clinical data of all included patients (*N* = 69, tested at T1) and of a subgroup (*n* = 31, tested at T1, T2, T3).

Variables	*N* = 69 (total)	*n* = 31 (subgroup)
Sex		
Male	42	18
Female	27	13
Age in years		
Mean T1 (range)	42.1 (20–74)	39.9 (20–60)
Mean T2 (range)	–	40.3 (21–40)
Mean T3 (range)	–	41.1 (21–61)
Education on Verhage scale[a]		
Mean (range)	5.4 (3–7)	5.5 (3–7)
Handedness		
Right	56	25
Left	10	6
Ambidexter	2	0
Unknown[b]	1	0
Tumour grade		
Low	41	19
High	15	7
Unknown[b]	13	5
Tumour location (hemisphere)		
Left	48	18
Right	16	9
Unknown[b]	5	4
Tumour location (lobe)		
Frontal	23	11
Combined (total)[c]	17	10
Non-frontal (total)	11	6
Temporal	3	2
Parietal	3	1
Insular	2	1
Combined[c]	3	2
Unknown[b]	21	6

Note: T1 = preoperatively, T2 = 3 months postoperatively, T3 = 1 year postoperatively, *N* = total number of patients (total sample), *n* = number of patients (subgroup).

[a]Education was classified according to the coding system of Verhage (1964), ranging from 1 (only primary school) to 7 (university degree).

[b]This information was not transferred to an electronic health record from the Erasmus MC and therefore not available to the authors.

[c]There is overlap between these categories.

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Assessment

All patients were individually tested with a comprehensive neuropsychological test protocol preoperatively: 1–2 months before surgery (T1), and a subgroup also postoperatively: at three months (T2) and one year (T3) after surgery as part of a clinical follow-up. The (full) protocol could not always be applied in some patients (e.g. fatigue, cognitive load, and lack of time) or at all three time points (e.g. disease severity, not willing to cooperate). The test protocol consisted of fluency tests, language tests, and executive functioning tests, as shown in Table 2 and discussed below.

Verbal fluency (category and letter fluency) and nonverbal fluency were administered in line with clinical standard practice as is still done in our hospital nowadays. In the category fluency tasks, patients were asked to generate as many words in a given category (animals, professions) within one minute. Category fluency tasks were used to examine the flexibility of semantic processing. The two semantic categories were kept as separate scores because Dutch norm data revealed different influences of age and sex in both categories (Van Der Elst et al., 2006). In the letter fluency tasks, patients were asked to name as many words starting with a given letter within one minute. Letter fluency tasks were used to examine the flexibility of phonological processing. All patients were assessed with three letters per time point, lasting one minute for each letter. Preoperatively, one patient was assessed with P-G-R and all others with D-A-T. Postoperatively, all patients were assessed with K-O-M. As is clinically standard, the scores on the three letters were combined to compute one score for letter fluency (Schmand et al., 2008).

For the nonverbal fluency test, the Five Point Test (FPT, Regard et al., 1982) was used. The patient was asked to draw as many unique figures in squares of five dots by connecting two or more dots with straight lines within three minutes (see Figure 1). This test was administered to examine multiple executive processes such as flexibility, strategy implementation, and rule-breaking. This test was also administered in the healthy control group. The number of unique words/designs was the fluency score used in this paper. Errors, such as perseverations, and strategy scores were not taken into account in this paper.

Additionally, the test protocol consisted of language tests. Phonology was examined with the repetition subtests of the Aachen Aphasia Test (AAT, Graetz et al., 1992). Language comprehension and the presence and severity of aphasia were examined with the Token Test (TT, De Renzi & Faglioni, 1978). Word-finding was examined with the Boston Naming Test (BNT, Kaplan et al., 2001).

Lastly, the test protocol consisted of executive functioning tests. Visuomotor speed and attention were examined with the Trail Making Test A, while concept shifting was examined with Trail Making Test B (Army Individual Test Battery, 1944). Inhibition and selective attention were examined with the Stroop Colour-Word Test (Stroop, 1935). Various executive processes such as switching were examined with the Modified Wisconsin Card Sorting Test (Nelson, 1976).

Statistical analyses

Statistical analyses were performed using SPSS version 25.0. *Z*-scores of all administered neuropsychological tasks were calculated based on normative Dutch data (ANDI norms 2.0.6-2020-12-12, Graetz et al., 1992) to control for demographic variables. Since no Dutch norms were available for nonverbal fluency, we collected data from a control group ($n = 27$) and calculated regression-based normative data. Variables (age, sex, educational level according to the scale of Verhage (1964) and more or less than 13 years) were checked for normality and Pearson's and Spearman's Rho correlations between the variables and nonverbal fluency scores were computed. Age, $r(25) = -.63$, $p = .000$ and educational level, Verhage; $r_s(25) = .44$, $p = .022$ correlated with the raw nonverbal fluency scores and they were entered as predictors in a linear regression model. Then the expected score (ES) and residue scores (RS) were calculated using the model's information: $ES = 29.75 + (-.305 \times x) + (3.363 \times y)$, RS = observed score of norm group-ES. The RS were converted to percentiles and z-scores (see Appendix S1). Means, standard deviations, and ranges were calculated for the z-scores of each test.

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TABLE 2 The neuropsychological test protocol.

Test	Cognitive abilities	Description
Verbal fluency		
Category fluency	Word retrieval, flexibility of semantic processing	Producing words of a given category within 1 min
Letter fluency	Word retrieval, flexibility of phonological processing	Producing words beginning with a given letter within 1 min
Language		
Aachen Aphasia Test (AAT): Repetition (Graetz et al., 1992)	Phonology	Repeating phonemes, words, and sentences
Token test (TT; De Renzi & Faglioni, 1978)	Language comprehension	Touching to and moving geometric forms on verbal commands
Boston Naming Test (BNT; Kaplan et al., 2001)	Word-finding	Naming 60 pictures presented in order of word frequency and difficulty
Executive functions		
Five Point Test (nonverbal fluency, Regard et al., 1982)	Various executive processes such as flexibility, strategy implementation, and rule-breaking	Drawing as many unique figures by connecting two or more dots with straight lines within 3 min
Trail Making Test (TMT) *TMTA*, *TMTB*, *TMTBA* (Army Individual Test Battery, 1944)	A: visuomotor speed; attention B: concept shifting B/A: mental flexibility	A: Connecting numbers placed randomly in ascending order as rapidly as possible B: Connecting alternating numbers and letters as rapidly as possible
Stroop Colour-Word Test *I*, *II*, *III*, *interference* (Stroop, 1935)	I: reading speed II: colour naming speed III: inhibition interference: selective attention	Reading colour words, naming colours & naming colours of printed words denoting another colour
Modified Wisconsin Card Sorting Test (MCST; Nelson, 1976)	Various executive processes such as switching	Sorting stimulus cards according to colour, symbol, or number of symbols

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To investigate verbal and nonverbal fluency performance of glioma patients at T1 (aim 1), we compared their fluency z-scores to the healthy population (i.e. normative Dutch data for verbal fluency and data from the healthy Dutch control group for nonverbal fluency). This contrast was computed for the whole patient sample ($N=69$), and for patient subgroups divided according to lesion location (frontal lobe $n=23$; non-frontal lobe $n=11$, including temporal = 3, parietal = 3, insular = 2, combined non-frontal = 3), and affected hemisphere (left-hemispheric tumours $n=48$; right-hemispheric tumours $n=16$). The analyses were conducted using one-sample t-tests and one-sample Wilcoxon signed-rank tests with 0 as the test value (based on normality tests). Additionally, the frequency of different levels of performance was counted (from excellent, $z>2.0$, to severely impaired, ≤ -2.0).

Next, we explored the influence of language, executive functioning, and demographic/clinical variables on verbal fluency performance at T1 for all glioma patients ($N=69$, aim 2). Pearson's and Spearman's Rho correlations (based on normality) were performed between the verbal fluency z-scores and (1) demographic and clinical information (sex, age, handedness, education according to the Verhage scale, tumour grade, tumour location: hemisphere, lobe) and (2) the other neuropsychological tests z-scores (see Table 2 for the test protocol). Multicollinearity was checked between the independent variables. Variables with a high correlation coefficient (>−.8/.8) were excluded (Field, 2013). Additionally, a theory-driven approach was used to further exclude variables based on logical assumptions (see Appendix S2 for more information on the selection process). This was done because we aimed to prevent inclusion of a large number of (illogical) noisy variables, especially because our patient group was relatively small. The selected independent variables were included in three separate linear regression models (with listwise exclusion) with the z-scores of category fluency animals, category fluency professions, and letter fluency as the dependent variables. Since this is an explorative study, all correlated variables were entered at once, resulting in one model for each dependent variable. To check once more for multicollinearity, variables with variable inflation factors (VIFs) higher than 5 were excluded. To gain more insight into the cognitive processes underlying impaired verbal fluency performance, the same regression analyses were performed for clinically impaired patient groups with category fluency animals ($n=16$), category fluency professions ($n=23$), and letter fluency ($n=22$) z-scores of ≤ -1.00.

Finally, we investigated the short and long-term effects of surgery on verbal and nonverbal fluency performance in a subgroup of patients ($n=31$, aim 3) and the effect of hemispheric tumour location (aim 4). Mixed Model Anovas were performed with time as a within-subject variable (T1, T2, T3), hemisphere (left, right) as a between-subject variable and fluency score (accuracy) as the dependent variable were performed with the raw fluency scores (one analysis per fluency task). Post-hoc analyses were done using paired-sample t-tests (T1–T2, T2–T3, T1–T3) and independent samples t-tests (T1, T2, T3).

RESULTS

Aim 1: Preoperative verbal and nonverbal fluency performance (T1)

The following results of glioma patients at T1 are all compared to the healthy population (compared to normative Dutch data for verbal fluency and a healthy Dutch control group for nonverbal fluency). Significant lower z-scores were found in glioma patients ($N=69$) on category fluency animals, $t(68)=-5.558$, $p<.001$, category fluency professions, $t(68)=-4.648$, $p<.001$, and letter fluency ($z=-2.942$, $p=.003$). No statistical difference between groups was found for nonverbal fluency scores, $t(68)=.000$, $p=1.000$, see Table 3. Additionally, significant lower z-scores were found in glioma patients with frontal tumour locations ($n=23$) on category fluency animals, $t(22)=-2.706$, $p=.013$) and in patients with non-frontal locations ($n=11$) on category fluency professions, $t(10)=-2.342$, $p=.041$. No significant differences were found for the other fluency tasks (see Appendix S3). In addition, significant lower z-scores were found in glioma patients with left-hemispheric tumours ($n=48$) in category fluency animals, $t(47)=-4.743$, $p<.001$, category fluency professions, $t(47)=-3.970$, $p=<.001$ and letter fluency, $t(47)=-4.187$, $p<.001$, and in patients with right-hemispheric tumours ($n=16$) in category

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TABLE 3 Preoperative (T1) performance in *z*-scores on the neuropsychological tests and comparisons to the healthy population.

Task	*Z*-scores				Compared to healthy population[a]		
	N/n	***M***	**Range**	***SD***	***t/z***	***p***	**Interpretation**
Fluency							
Category fluency animals	69	−.70	−3.88 to 1.54	1.04	$t(68) = -5.558$	<.001	Lower
Category fluency professions	69	−.67	−3.82 to 3.34	1.19	$t(68) = -4.648$	<.001	Lower
Letter fluency	69	−.54	−4.47 to 1.42	1.25	$z = -2.942$	.003	Lower
Nonverbal fluency	69	.00	−2.44 to 2.44	1.00	$t(68) = .000$	1.000	No difference
Language							
Repetition (AAT)	69	.29	−4.48 to .73	.77	$z = 4.975$	<.001	Higher
Token Test	69	−.05	−.83 to 4.26	1.11	$z = -2.880$	.004	Lower
Boston Naming Test	69	−.87	−3.17 to .96	1.00	$t(68) = -7.189$	<.001	Lower
Executive functioning							
Trail Making A	69	−.39	−3.10 to 2.00	1.15	$t(68) = -2.832$	.006	Lower
Trail Making B	69	−.48	−4.40 to 2.00	1.49	$z = -1.846$	.065	No difference
Trail Making B/A	69	−.29	−4.40 to 3.00	1.51	$z = -.572$	.567	No difference
Stroop I	59	−.85	−4.10 to 2.00	1.44	$t(58) = -4.516$	<.001	Lower
Stroop II	59	−.68	−3.40 to 1.90	1.15	$t(58) = -4.519$	<.001	Lower
Stroop III	59	−.65	−3.90 to 2.90	1.28	$z = -3.454$	<.001	Lower
Stroop interference	59	−.31	−4.40 to 1.80	1.29	$z = -1.197$	.231	No difference
Modified Wisconsin Card Sorting Task	56	−.33	−3.10 to .80	.91	$z = -1.086$	.277	No difference

Note: N = total number of patients (total sample), n = number of patients (subgroup).

Abbreviations: M, mean; SD, standard deviation.

[a]Comparisons were made to the healthy population: nonverbal fluency was compared to a healthy Dutch control group while verbal fluency and all other neuropsychological tests were compared to normative Dutch data, with one-sample *t*-tests (*t* value) and one-sample Wilcoxon signed-rank tests (*z* value) with 0 as the test value.

fluency animals, $t(15) = -2.590$, $p = .021$ and professions, $t(15) = -2.468$, $p = .026$. No significant differences were found for the other fluency tasks (see Appendix S3).

Looking at all patients ($N = 69$) at the individual level at T1, severe impairments ($z \leq -2.00$) were most often found in category fluency professions ($n = 10$) and letter fluency ($n = 8$), and mild impairments ($z \leq -1.00$) in category fluency animals ($n = 19$, see Figure 2).

Additionally, at T1, patients scored significantly lower than the healthy population on the Token Test, BNT, Trail Making Test A, and Stroop I, II, and significantly higher on repetition (see Table 3). No differences between groups were found on Trail Making Test B, Trail Making Test B/A, Stroop interference, and the Modified Wisconsin Card Sorting Test.

Aim 2: The influence of language and executive functioning on verbal fluency (T1)

Z-scores of all preoperative neuropsychological tests are shown in Table 3 ($N = 69$). Independent variables for the models were selected based on significant correlations with the dependent variable, correlation coefficients between the independent variables, logical assumption, and VIF. An example of exclusion by logical assumptions is that repetition, a test to assess phonology, would not be included in the model for category fluency considering that category fluency is not a phonological test (see Appendix S2 for the selection process for each model).

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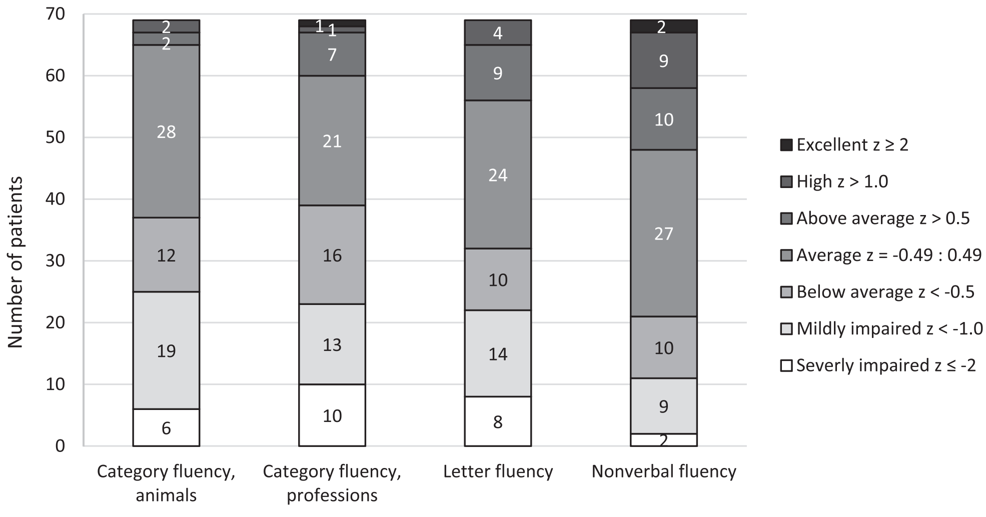

FIGURE 2 Performance in *z*-scores of glioma patients on verbal fluency and nonverbal fluency at T1 ($N=69$).

Performances on BNT ($B=.240$, $p=.046$), nonverbal fluency ($B=.455$, $p<.001$), and Stroop III ($B=.211$, $p=.022$, see Table 4) were significant predictors for category fluency animals performance and the Modified Wisconsin Card Sorting Test ($B=.218$, $p=.058$) showed a trend towards significance (all VIF statistics were <1.484). No significant predictors were found for category fluency professions, but TT performance showed a trend towards significance ($B=-.286$, $p=.069$, all VIF statistics were <1.200). Performances on TT ($B=-.500$, $p=.023$) and nonverbal fluency ($B=.386$, $p=.013$) were significant predictors for letter fluency performance (all VIF statistics were <2.838) and hemispheric tumour location showed a trend towards significance ($B=-.694$, $p=.069$). These results are summarized in Figure 3.

Tumour grade ($B=-.588$, $p=.046$) was a significant predictor in the regression model for patients with clinically impaired scores ($z\leq-1.00$) on category fluency animals ($n=16$, see Table 4, all VIF statistics were <1.514). Token Test performance ($B=-.284$, $p=.022$) was a significant predictor in the regression model for patients with clinically impaired scores ($z\leq-1.00$) on letter fluency ($n=22$, all VIF statistics were 1.031). The regression model for clinically impaired scores in category fluency professions ($n=23$) did not reach significance (model: $p=.174$, see Appendix S4 for the model).

Aim 3 & 4: Verbal and nonverbal fluency performance: The effects of surgery and hemispheric tumour location (T1, T2, T3)

The effects of surgery and hemispheric tumour location on verbal and nonverbal fluency were also examined longitudinally in a subgroup of patients ($n=31$) across three assessment time points: preoperatively (T1), and 3 months (T2) and 1 year postoperatively (T3, see Table 1). A significant main effect of time was found for category fluency professions, $F(2, 50)=4.148$, $p=.022$. A significant decline in category fluency professions was found between T1 and T2, $t(30)=2.453$, $p=.020$ and between T1 and T3, $t(30)=2.752$, $p=.010$, while no differences in category fluency professions were found between T2 and T3, $t(30)=-.128$, $p=.899$, see Figure 4). No main effects of time were found for category fluency animals, $F(2, 50)=.708$, $p=.497$ and letter fluency, $F(2, 50)=.190$, $p=.828$.

A significant main effect of time was also found for nonverbal fluency, $F(2, 36)=8.775$, $p<.001$. While no differences in nonverbal fluency were found between T1 and T2, $t(29)=-1.911$, $p=.066$, significant improvements were found between T1 and T3, $t(23)=-4.056$, $p<.001$ and T2 and T3, $t(23)=-2.250$, $p=.034$, see Figure 4.

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TABLE 4 Linear models of predictors of category fluency animals ($n = 51$), category fluency professions ($n = 59$), letter fluency ($n = 56$), impaired category fluency animals ($z \leq -1.00$, $n = 16$) and impaired letter fluency ($z \leq -1.00$, $n = 22$).

	CF animals ($n = 51$)			CF professions ($n = 59$)			Letter fluency ($n = 56$)			CF animals (clinically impaired, $n = 16$)			Letter fluency (clinically impaired, $n = 22$)		
	B	*SE*	*β*	*B*	*SE*	*β*	*B*	*SE*	*β*	*B*	*SE*	*β*	*B*	*SE*	*β*
Constant	−.236	.173		−.635	.170		1.047	1.007		−.791	.371		−1.601	.206	
Language															
Boston Naming Test	**.240***	.117	.226	–	–	–	–	–	–	–	–	–	–	–	–
Repetition	–	–	–	–	–	–	−.281	.381	−.139	–	–	–	–	–	–
Token Test	−.126	.106	−.132	−.286	.154	−.240	**−.500***	.214	−.416	−.240	.178	−.0472	**−.284***	.114	
EF															
Nonverbal fluency	**.455****	.114	.456	.143	.156	.122	**.386***	.150	.325	.037	.135	.055	.342	.184	.341
Trail Making A	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Trail Making B	−.111	.080	−.155	–	–	–	−.082	.122	−.094	–	–	–	–	–	–
Stroop I	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Stroop II	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Stroop III	**.211***	.089	.281	.145	.125	.160	.144	.132	.154	−.062	.118	−.127	–	–	–
Stroop Interference	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Modified Card Sorting Task	.218	.112	.206	–	–	–	–	–	–	–	–	–	–	–	–
R^2	.580			.139			.399			.631			.379		
Demo/clinical information															
Handedness	–	–	–	–	–	–	−.227	.380	−.091	–	–	–	–	–	–
Hemisheric tumour location	–	–	–	–	–	–	−.694	.373	−.245	–	–	–	–	–	–
Tumour grade	–	–	–	–	–	–	–	–	–	**−.588***	.261	−.472	–	–	–

Note: n = number of patients (subgroup, it differs per regression due to the use of listwise exclusion of missing data) – = not part of the model (see Appendix S2 on information on variable selection). Impaired category fluency professions are not shown here because the model did not reach significance (see Appendix S4 for the model). Bold shows a significant result.

Abbreviations: CF, category fluency; EF, executive functioning.

$^{*}p < .05$; $^{**}p \leq .01$.

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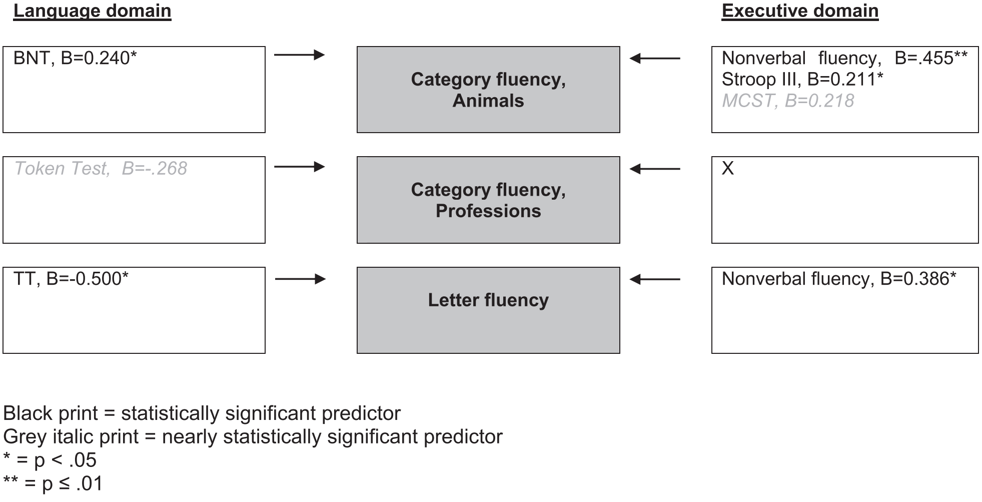

FIGURE 3 Predictive tasks for verbal fluency performance. Black print = statistically significant predictor. Grey italic print = nearly statistically significant predictor. *$p < .05$. **$p \leq .01$.

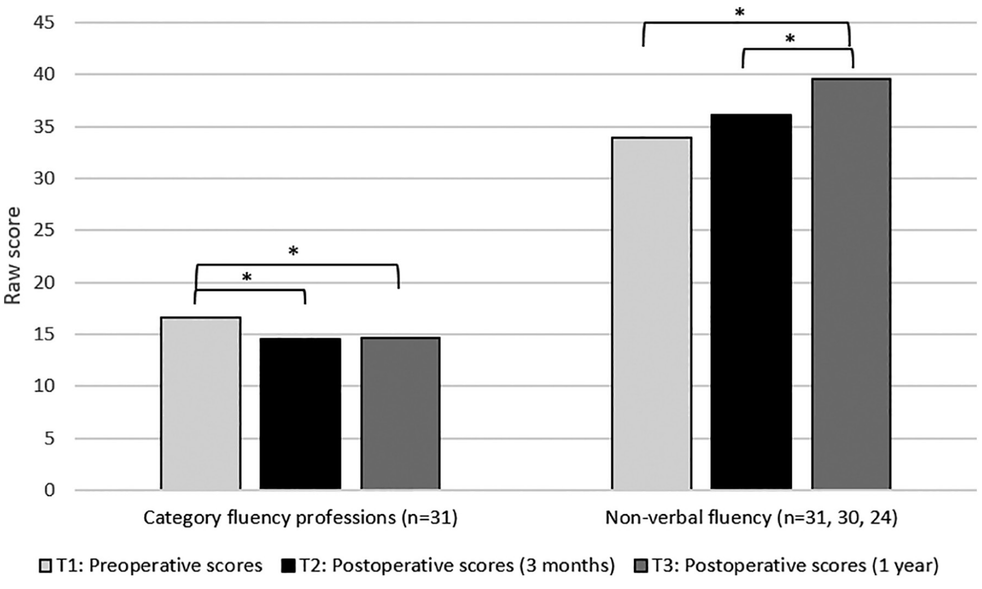

FIGURE 4 The short and long-term effects of surgery on raw scores of verbal fluency and nonverbal in the subgroup ($n = 31$). *Significant difference ($p < .05$). T1 = preoperatively, T2 = postoperatively (3 months), T3 = postoperatively (1 year).

A significant main effect of hemispheric tumour location was found for letter fluency, $n = 27$, $F(1, 25) = 13.064$, $p = .001$. Significant lower raw scores on letter fluency were found in patients with tumours in the left hemisphere compared to patients with tumours in the right hemisphere at T1, $t(25) = 2.342$, $p = .027$, T2, $t(25) = 3.928$, $p = .001$, and T3, $t(25) = 3.394$, $p = .002$, see Figure 5. No significant effect of hemispheric tumour location was found for category fluency animals, $F(1, 25) = .003$, $p = .960$, category fluency professions, $F(1, 25) = .001$, $p = .970$, and nonverbal fluency, $F(1, 18) = .661$, $p = .427$.

No significant interaction effects (time-hemisphere) were found for category fluency animals, $F(1, 25) = .006$, $p = .940$, category fluency professions, $F(1, 25) = 2.359$, $p = .137$, letter fluency, $F(2, 50) = 2.996$, $p = .059$ and nonverbal fluency, $F(2, 36) = .671$, $p = .518$.

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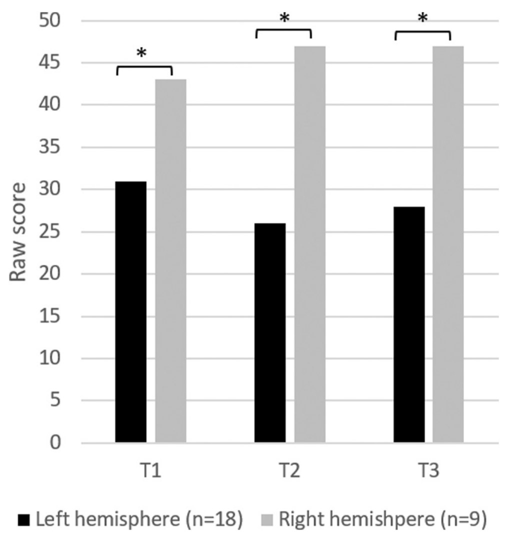

FIGURE 5 Performance on letter fluency divided by hemispheric tumour location at different time points in the subgroup (n = 27). *Significant difference (p < .05), T1 = preoperatively, T2 = postoperatively (3 months), T3 = postoperatively (1 year).

DISCUSSION

Preoperative verbal and nonverbal fluency performance (T1)

We investigated the preoperative verbal and nonverbal fluency performance in glioma patients compared to the healthy population (compared to normative Dutch data for verbal fluency and a healthy Dutch control group for nonverbal fluency). All verbal fluency tests (category fluency animals, category fluency professions, and letter fluency) were sensitive to find clinical deviations at group level, whereas nonverbal fluency was not impaired, which is in line with our expectations and the literature (Goldstein et al., 2004; Racine et al., 2015; Satoer et al., 2012; Zigiotto et al., 2022).

It was expected that especially letter fluency would be impaired in patients with frontal tumours, but we found that these patients only showed significant impairment in category fluency animals. Previous studies in patients with frontal lesions also found impairments in category fluency animals (Baldo et al., 2001), or lower scores in category fluency animals in frontal patients compared to non-frontal patients (Zienius et al., 2022). However, these studies also find these results for letter fluency, while we did not find a relation between frontal areas and letter fluency. Interestingly, the lack of frontal involvement in letter fluency performance has also been reported by Chouiter et al. (2016), who mainly found involvement of the basal ganglia, superior temporal gyrus, supramarginal gyrus, and rolandic operculum. Perhaps that the lack of letter fluency impairment in our patients with frontal gliomas can be linked to intactness of subcortical language tracts such as the frontal aslant tract, considering that a relation between this tract and letter fluency has been reported (Landers et al., 2022; Zigiotto et al., 2022).

For patients with non-frontal tumours, it was expected that they would be impaired in category fluency. Results show that they were impaired in category fluency professions only, which is not surprising because professions seems more difficult than animals (discussed below). Thus, our results seem to be in line with the literature stating that category fluency (in this case professions specifically) relies on non-frontal brain regions (Zigiotto et al., 2022).

It may seem surprising that frontal and non-frontal glioma patients showed different deficit patterns relative to healthy individuals across semantic categories, since we detected impaired retrieval of animals in frontal glioma patients and impaired retrieval of professions in non-frontal glioma patients.

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These differences may be explained by the fact that other categories than animals are reported to be represented in more widespread brain locations or networks (Diesfeldt et al., 2009), thus yielding different results concerning impairment based on tumour location. Also, the result that category fluency animals were impaired in frontal glioma patients may be due to more reliance of this category on executive processes such as switching (see also Aim 2: The influence of language and executive functioning on verbal fluency (T1) section), which is supported by the frontal lobe.

As expected, patients with left-hemispheric tumours showed impairments in all verbal fluency measures. In contrast, patients with right-hemispheric tumours showed impairments in category fluency only. This suggests that letter fluency specifically seems to rely on the left hemisphere, as indicated before (Biesbroek et al., 2016), possibly reflecting more reliance on phonological processing which is assumed to be more left-lateralized (Hickok & Poeppel, 2007). In contrast, our result suggests that category fluency seem to rely on both hemispheres in this glioma patient group, possibly reflecting more reliance on lexical-semantic processing, which is more bilaterally supported (Hickok & Poeppel, 2007).

Involvement of the right hemisphere in category fluency has been reported before, for example in stroke patients by Biesbroek et al. (2016). They suggest this right involvement may implicate the use of a strategy for mental imagery. Another study on language testing in glioma patients using the Diagnostic Instrument for Mild Aphasia (DIMA, Satoer et al., 2022), which includes subtests under time pressure, also showed impairments in left-hemispheric and right-hemispheric glioma patients (Mooijman et al., 2021). This suggests that some language tests with time pressure such as subtests from DIMA or category fluency are sensitive in all glioma patients independent of hemispheric tumour location.

At the individual level, severe impairments were most often found in category fluency professions compared to the other fluency tasks, suggesting that this task is the most sensitive to detect impairments out of the investigated fluency subtests. Additionally, this also seems to suggest that category fluency professions is more difficult than other fluency tasks for glioma patients, which is also the case for Dutch healthy controls, who scored lower on category professions than animals (Schmand et al., 2008, 2012).

Severe impairments in nonverbal fluency occurred in only two cases, which showed that severe impairments were least often found in nonverbal fluency compared to the other fluency tasks. These results indicate that there are discrepancies between verbal and nonverbal fluency, which has been found before in other patient groups, such as in patients with early-onset schizophrenia (Phillips et al., 2004).

Aim 2: The influence of language and executive functioning on verbal fluency (T1)

We explored the influence of language, executive functioning, and demographic/clinical factors on verbal fluency performance in all glioma patients at the preoperative time point (T1). Our results suggest that verbal fluency scores in glioma patients were predicted by both language and executive functioning test scores, corroborating previous findings that both domains are involved in verbal fluency in healthy participants (Aita et al., 2018; Patt et al., 2017). More specifically, performances on category fluency animals and letter fluency were significantly predicted by different language and executive functioning tests, while no significant predictors were found for category fluency professions.

In the language domain, BNT statistically predicted the performance on category fluency animals. This is not surprising since the BNT is a robust test for word retrieval, which is also needed in fluency. In contrast, the BNT was not a predictor for category fluency professions performance. Moreover, even though another language-related test showed a trend towards significance (the Token Test), no significant language predictors were found for category fluency professions (discussed below).

The Token Test was a significant predictor for letter fluency. The Token Test assesses language comprehension and determines the presence and severity of aphasia. However, it is not a pure measure of language, since executive functioning processes such as working memory also contribute to test performance (Basagni et al., 2022). This result seems to indicate that working memory is more

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involved in letter fluency than in category fluency. The involvement of more working memory in letter fluency seems logical, considering that one needs to remember all individual named words, which are not clustered (Azuma et al., 1997), to make sure no duplicates are named. This is in contrast to semantic fluency, in which words are clustered in subcategories (Azuma et al., 1997) and in which retaining the subcategory would be enough (retaining only "pets") instead of all individual named words. This seems easier and may require less working memory.

While a correlation between repetition (AAT) and letter fluency was found, which resulted in repetition being part of the model for letter fluency, repetition performance was not a predictor. This is surprising because both tests are often indicated as phonological tests (De Witte et al., 2015). This could be because the repetition task was not sensitive: patients performed even *better* compared to the healthy population ($M = .29$). Thus, a ceiling effect occurred leading to limited variability in the data. This may be caused by the fact that this repetition test, from the AAT, was developed for stroke patients (Graetz et al., 1992). Therefore, it may not be sensitive enough for glioma patients. It would be interesting to investigate whether there is a predictive relation between sensitive repetition tasks specifically designed for glioma patients, such as from the DIMA, and letter fluency performance.

In the executive domain, nonverbal fluency performance statistically predicted the performance on category fluency animals and letter fluency. Nonverbal fluency measures several executive processes such as cognitive flexibility, strategy implementation, and rule-breaking (Goebel et al., 2009), of which some or all support performances on category fluency animals and letter fluency. Stroop III, a task that assesses inhibition, also significantly predicted category fluency animals, while the Modified Wisconsin Card Sorting Task (WCST) showed a trend towards significant prediction. The WCST measures processes such as switching (or shifting, Grant & Berg, 1948; Heaton, 1980), which is needed in category fluency to switch from one subcategory to another (e.g. "pets" to "zoo animals"). It seems logical that switching and also clustering are more relevant in category fluency animals, because it may be easier to form larger clusters and switch to other subcategories considering that there are many subcategories in animals.

Surprisingly, no significant predictors were found for category fluency professions. Perhaps this is due to the fact, as already mentioned above, that words for professions are represented in widespread brain locations, in contrast to words for animals that are represented in a specific brain area in the frontotemporal cortex (Diesfeldt et al., 2009). Perhaps this more widespread neural representation of words for professions also results in category fluency professions being influenced by other processes that we have not included in this study. The range of tests in the current paper was thus limited. Other tests, assessing other processes and similar processes more in depth, should be included to shed more light on the underlying mechanisms needed to perform the verbal fluency tests. Especially focusing on executive functioning tests, measures of working memory, such as the forward digit span, backward digit span, backward visuospatial span, and the letter-number sequencing task (WAIS), could be investigated in glioma patients since they were predictive for verbal fluency scores in patients with schizophrenia and frontotemporal dementia (Laisney et al., 2009; Ojeda et al., 2010). It can also be useful to look at other processes in glioma patients such as verbal intelligence, processing speed, and psychomotor speed, since these predicted verbal fluency scores in healthy controls (Stolwyk et al., 2015) and schizophrenic patients (Van Beilen et al., 2004).

Hemispheric tumour location showed a trend towards significantly predicting letter fluency performance. This is in line with our results indicating the relation between the left hemisphere and letter fluency (aim 1) and concerning lower letter fluency scores in left-hemispheric glioma patients compared to right-hemispheric glioma patients over time (aim 3). However, this result from the regression was not significant. Moreover, none of the demographical and clinical variables had a significant influence on the verbal fluency scores in our data when investigating all patients. The lack of relation in our data may be explained by minimal variance in some variables. For example, low education levels, left-handedness, high-grade tumours, and right-hemispheric tumours were underrepresented in this study. Also, some tumour location groups were very small (e.g. temporal: $n = 3$, parietal: $n = 3$). Therefore, we could only group these locations in the non-frontal group instead of investigating these specific lobes.

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We also investigated the influence of language and executive functioning on verbal fluency performance in patients with clinically impaired scores ($z \leq -1.0$). In contrast to the results for all patients, tumour grade was a significant predictor for clinically impaired category fluency animals performance, indicating that a higher tumour grade related to a lower score on this test. Lower scores on language tests in high-grade compared to low-grade glioma patients have been found before (Noll et al., 2015) and could be explained by differences in neuroplasticity. The slow tumour growth of low-grade gliomas generally results in more functional compensation compared to the aggressive fast-growing high-grade gliomas (Cirillo et al., 2019).

Additionally, the Token Test was a predictor for clinically impaired category letter fluency performance. This is in line with the results for letter fluency performance in the total patient group. More clinically impaired patients should be investigated to see whether these effects are robust. The lack of more significant results in the clinically impaired group may be explained by the small number of patients in each group, n(animals) = 16, n(professions) = 23, n(letter) = 22.

Aim 3: Verbal and nonverbal fluency performance: The effects of surgery (T1, T2, T3)

We also investigated the effect of surgery on verbal and nonverbal fluency performance and the relation to hemispheric tumour location in a subgroup of glioma patients who were tested at three time points (T1, T2, T3). Since no interaction effects were found between time and hemispheric tumour location, these results will be discussed separately for clarity.

Time, and thus surgery, had a significant effect on category fluency professions and nonverbal fluency. Partially in line with our expectations and Satoer et al. (2014), we found a short-term postoperative decline for category fluency professions (T1–T2). Moreover, this decline in category fluency professions persisted in the long-term (T1–T3). Therefore, this test seems sensitive to detect more permanent impairments. No effect of surgery was found for category fluency animals or letter fluency. This discrepancy between tasks may be caused by differences in complexity between the verbal fluency tasks.

Time, and thus surgery, also had a significant effect on nonverbal fluency. The reverse pattern occurred for nonverbal fluency: patients were not impaired and even performed better at the long-term follow-up (T1–T3, T2–T3). Hence, it appeared that surgery had a positive influence on nonverbal fluency performance, which suggests that awake surgery can not only maintain but also improve cognitive functioning. This pattern of improved postoperative nonverbal fluency performance seems to be novel. However, postoperative improvement between a week and three months in executive functioning has previously been found with the Trail Making Test Ratio, assessing cognitive flexibility (Papagno et al., 2012).

The postoperative improvement in nonverbal fluency may be explained by tumour location. Nonverbal fluency is assumed to rely on the left and right frontal lobes (Baldo et al., 2001; Elfgren & Risberg, 1998). Out of the 31 patients in the subgroup, 61% had (partial) frontal tumours in the left or right hemisphere. The lack of preoperative impairment on group level in nonverbal fluency (see Preoperative verbal and nonverbal fluency performance (T1) section) may be caused by contralateral frontal compensation. Postoperatively, tumour resection in the frontal lobe (especially of higher graded tumours) may have alleviated mass effect and induced further postoperative neuroplasticity, resulting in improvement in nonverbal fluency.

Aim 4: Effects of hemispheric tumour location on verbal and nonverbal fluency (T1, T2, T3)

Hemispheric tumour location had a significant effect on letter fluency performance in a subgroup of glioma patients (n = 31) who were tested at three time points (T1, T2, T3). Patients with left-hemispheric

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tumours scored lower than patients with right-hemispheric tumours on letter fluency preoperatively (T1) and postoperatively on the short- and long-term (T2, T3). This is in accordance with our expectations since verbal fluency seems to rely more on the left hemisphere, as previously reported (Biesbroek et al., 2021) and also found by this study (only patients with left-hemispheric tumours and not right-hemispheric tumours were impaired in letter fluency, see Aim 1: Preoperative verbal and nonverbal fluency performance (T1) section). This may also be related to subcortical networks considering that specific left pathways have been indicated to relate to verbal fluency (Zigiotto et al., 2022). However, we expected an overall effect on all verbal fluency tasks. The absence of an effect of hemispheric tumour location for the category fluency tasks may be due to involvement of both left and right hemispheres in category fluency in this patient group (see Aim 1: Preoperative verbal and nonverbal fluency performance (T1) section). If both hemispheres are involved, it is not surprising that no differences are found between hemispheres. Additionally, our hypothesis concerning nonverbal fluency was based on the result by Baldo et al. (2001), who did not find any difference in nonverbal fluency performance between hemispheres. In line with this, we did not find hemispheric differences in nonverbal fluency.

Clinical relevance

At group level, glioma patients were impaired in all three verbal fluency measures, showing that these tests are sensitive for this clinical population. In glioma patients, verbal fluency can be administered to get more insight into different possible underlying language and/or executive functioning deficits, depending on which verbal fluency task is selected. The order of neuropsychological tests could be determined based on differences in complexity as found by this study (i.e. category fluency profession is more difficult than animals), which could make the testing procedure more efficient. Additionally, category fluency professions can be selected up until a year after surgery to detect more permanent long-term deficits.

Since verbal fluency is a sensitive test, it could also be used as a screening tool during the resection stage of awake brain surgery in a shortened form without time pressure to prevent additional stress. Perhaps a rule for a (lower) number of intraoperative items can be developed taking the preoperative performance into account. Performance on this quick verbal fluency screening can give an initial understanding of fluency of the patient, which can lead to administering more tests to further investigate possible deterioration.

Limitations and future research

Limitations of this study are that there were missing data (demographical and clinical variables) and that we did not have any data on subcortical pathways. The integrity and location of pathways in relation to the tumour may have influenced the results, considering that close proximity of a glioma to language tracts can cause poorer verbal fluency performance (Landers et al., 2022). Future research could take the integrity of pathways and the proximity to the tumour into account when investigating predictors for verbal fluency further.

Another limitation is that the patient groups were not balanced in terms of some clinical and demographic variables (such as hemispheric tumour location) and that the impaired groups were small. Additionally, the test protocol may not have been extensive or sensitive (e.g. in the case of the repetition task) enough.

To investigate the specific processes of language and executive functioning further, future qualitative research is needed, especially to investigate category fluency professions. It should elaborate on the used words, error types, and strategies rather than the number of produced words only. For example, the produced words can be clustered, which is when words of the same semantic or phonemic category are used in a row. When a cluster is depleted, a new search is initiated, which is called switching.

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Investigating clustering and switching may give insight into the underlying strategies within the language and executive functioning domains, as it has in other neurological populations such as in patients with frontotemporal dementia and primary progressive aphasia (Van den Berg et al., 2017, 2022). Strategies will likely differ for letter fluency and category fluency, and even between categories and compared to healthy controls. More insight into these strategies may contribute, among other factors and test results, to selecting a specific type of therapy based on language, executive functioning, or both domains. Training the impaired domain or specific process can result in improvement in that domain or process, which can improve quality of life in glioma patients.

Additionally, the prognostic value of verbal fluency can be investigated as a continuation of previous promising work. For example, Zienius et al. (2022) recently showed that preoperative category fluency animal performance can help discriminate between patients, who are experiencing the non-specific symptom of headache, with a brain tumour (51% gliomas) and those without a brain tumour. They suggest that category fluency animals can be administered when patients with a headache come to their primary care doctor and that performance on the test could facilitate decision-making concerning possible urgent brain imaging. If patients who truly have a tumour are scanned earlier, clinical care can be provided faster which can have positive effects on patient outcomes. Additionally, studies showed that postoperative verbal fluency performance in patients with low-grade (Papagno et al., 2012) and high-grade gliomas (Zarino et al., 2020) predicted tumour reoccurrence. It was not clear which categories were used in category fluency for these studies. Since we showed that category fluency professions seem to be a very sensitive verbal fluency task, further research should investigate the prognostic value of specifically category fluency professions performance on possible brain tumour diagnosis and tumour reoccurrence.

CONCLUSION

This study shows that verbal fluency is a sensitive task to detect cognitive deficits in glioma patients, while nonverbal fluency is not. Dissociations in verbal fluency performance were found based on frontal (impaired category fluency animals) versus non-frontal tumour locations (impaired category fluency professions) and left-hemispheric (impaired category fluency animals, professions, letter fluency) versus right-hemispheric tumour locations (impaired category fluency animals, professions).

The main result is that verbal fluency performance can provide information on different possible underlying deficits in language *and* executive functioning in glioma patients, depending on which verbal fluency task is selected. Efficient task (order) selection can be based on differences in verbal fluency task complexity and category fluency professions can be selected to detect more permanent long-term deficits. Qualitative research is needed to better understand the underlying strategies used to perform verbal fluency.

AUTHOR CONTRIBUTIONS

D.S., E.B. and E.C. contributed to the conceptualization and analysis. E.C. contributed to the writing—original draft preparation. All authors contributed to the writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Ellen Collée https://orcid.org/0000-0003-2794-4127

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Appendix S1.

Appendix S2.

Appendix S3.

Appendix S4.

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