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Research article

Overtaking in Stuttgart—analysis of the lateral distances between motor vehicles and bicycle traffic with reference to traffic volume and cycling infrastructure

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Abstract: In the context of climate change, it is desirable to increase the share of cycling. One way of doing this can be to strengthen subjective safety of cyclists. At present, many people perceive cycling as unsafe. In particular, overtaking by motor vehicles is a cause of low subjective safety and stress. In built-up areas, German road traffic regulations stipulate a minimum lateral distance of 1.50 m for motor vehicles, while overtaking cyclists. Previous research has shown that this rule is often not followed by motor vehicles. The aim of this study is to find out which factors influence the lateral distance of overtaking manoeuvres. The lateral distances of 4 081 overtaking manoeuvres were recorded using an ultrasonic sensor on 14 selected routes in the city of Stuttgart, Germany. 42% of the recorded overtaking manoeuvres were carried out with a lateral distance of less than 1.50 m. The mean value of all overtaking manoeuvres was 1.59 m. On roads with mixed traffic, higher lateral distances occurred than on roads with cycle lanes. In Germany, the motor vehicle traffic volume on a road is a key criterion for planning cycling infrastructure. However, it is not possible to confirm an influence of the motor vehicle traffic volume on the occurring lateral distances. The time of day at which overtaking manoeuvres take place also seems to have no effect on lateral distances.

Keywords: bike lanes, cycling infrastructure, overtaking, traffic volume

1 Introduction

Cycling is considered to be a climate friendly means of transport. It also promotes the health of its users and is comparatively inexpensive to use (Umweltbundesamt, 2022). However, cycling only accounts for a small proportion of total traffic in Germany. In 2017, only 11% of all trips in Germany were made by bicycle. In 2002, the figure was 9% (Nobis, 2019). Especially in view of the ongoing climate change, it is desirable to further increase the share of cycling. This is also the goal of the German Federal Ministry of Digital Affairs and Transport (BMDV), which wants to gradually promote the use of bicycles until 2030 (BMDV, 2022).

This raises the question of how to motivate more people to cycle. Among a number of potential barriers, the issue of cyclists' safety seems particularly relevant.

Compared to other road users, cyclists currently have an above-average risk of being involved in road traffic accidents (Alrutz et al., 2015). This affects the perception of cycling. Lack of safety is often cited as a reason why people do not cycle (Sinus Institut, 2021). Conflicts can always occur when motor vehicles (MV) and cyclists meet on a shared carriageway. Accidents between MVs and cyclists are most likely to occur at junctions. Overtaking manoeuvres (OM) are not among the main causes of cycling accidents. Nevertheless, the latter are perceived by cyclists as particularly dangerous and stressful (Richter et al., 2019; Merk et al., 2021).

For several years, German road traffic regulations (Straßenverkehrsordnung) have required MVs to leave a sufficient distance when overtaking cyclists. However, the amount of this lateral distance was originally not specified. This was changed in 2020. Since then, a lateral distance of at least 1.50 m in built-up areas and 2.00 m outside of built-up areas has been prescribed (Bundesgesetzblatt, 2020). In practice, many cyclists continue to report a high number of OMs in which overtaking MVs do not observe the prescribed lateral distance (Reutter, 2021).

However, it is not easy to verify this perception. Devices to measure lateral distance are not commercially available. For this reason, the topic has been the subject of increasing research in recent years. Tagesspiegel (n/d) equipped 100 test persons with ultrasonic measuring devices and analysed their daily trips. In total, 56% of all OMs were performed under 1.50 m. DHBW Stuttgart (Plavec & Schmock, 2021) used a similar approach, with over 100 test persons. Here, 74% of the OMs were below 1.50 m. Koppers et al. (2021) performed observations in traffic and determined a value of 43% for lateral distances below 1.50 m. Richter et al. (2019) performed laser measurements in real traffic and determined a value of 50% for too close OMs. Langer (2016) investigated lateral distances with one test person and camera observation. Overall, the subject was overtaken at a distance lower than 1.50 m in 75% of all OMs. In summary, the recorded lateral distances vary between different studies. However, all studies show that at least 43% of OMs are performed to close. This must be considered problematic, as it is likely to reduce bicycle safety.

Studies show some of the influencing factors of lateral distances. Cyclists are being overtaken particular close by MVs when there is oncoming traffic (Koppers et al., 2021; Langer, 2016; Merk et al., 2022). The same can be said when a road has cycle lanes (Langer, 2016; Mros, 2021; Ohm et al., 2015). The width of the carriageway seems to have an influence, with smaller lateral distances on narrower carriageways (Langer, 2016; Merk et al., 2022; Ohm et al., 2015). Cyclist behaviour also affects lateral distances. Narrow OMs occur more frequently the slower cyclists ride (Tagesspiegel, n/d; Plavec & Schmock, 2021) and the further apart they ride from the roadside (Mros, 2021; Richter et al., 2019).

Research has not yet determined the influence of MV traffic volume on OMs. In Germany, this value is a basic input variable for the selection of bicycle infrastructure for a road. The higher the MV traffic volume during peak hour, the more likely cycling and motor traffic are to be separated (FGSV, 2010). So far it is unclear whether this requirement can be derived from a correlation between MV traffic volume and the lateral distances that occur. This study therefore addresses three research questions:

1. Does cycling infrastructure have an influence on the lateral distances between MVs and cyclists?

2. Does MV traffic volume have an influence on the lateral distances between MVs and cyclists?

3. Does time of day have an influence on the lateral distances between MVs and cyclists?

Previous research shows an influence of cycle lanes on lateral distances. Therefore, research question 1 serves as a check on the methodology of this study. Research question 2 examines whether MV traffic volume is a valid basic input variable for bicycle infrastructure planning. Accordingly, research question 3 examines whether the focus on peak hours should be questioned.

2 Methodology

2.1 Data collection

The data was collected on trips undertaken specifically for this purpose, in the City of Stuttgart, Germany. The author of this paper was the only test person. This makes it possible to collect data on systematically selected streets. Also, due to a consistent riding style, comparability of the data among each other is ensured. The data was collected using a device called OpenBikeSensor. This device was developed by a group of activists in Stuttgart and measures lateral distances using ultrasound OpenBikeSensor (n/d).

In the course of this project, a total of around 790 km were covered and 4 081 OMs were recorded on 14 measurement routes. On all routes, cycling traffic is guided either in mixed traffic or on cycle lanes. German guidelines distinguish between two types of cycle lanes. Cycle lanes with dotted lines are not mandatory for cyclists and may be used by MVs under certain circumstances. Their regular width is 1.50 m and their minimum width is 1.25 m. Dotted cycle lanes are considered to be part of the carriageway. Cycle lanes with solid lines must be used by cyclists and may not be used by MVs. Their minimum width is 1.85 m. Solid cycle lanes are not part of the carriageway, but rather a separate path.

Both types of cycle lanes were included in the survey (see Table 1). Routes were chosen to be as similar as possible in design to the German guidelines. The roads did not have to be part of a designated cycle network. Existing traffic counts were required for selection. This data was provided by the city of Stuttgart. The traffic counts on hand do not contain sufficient information on bicycle volumes. Therefore, bicycle volume was not part of the analysis.

Table 1 Selected measurement routes

Name	Guidance form	MV volume
Augsburger Straße	CL(s)	1 147
Imweg	CL (d)	1 107
Fellbacher Straße	CL(d) / MT	809
Hegelstraße	MT	919
Rosenbergstraße	MT	799
Olgastraße (south)	CL(d) / MT	697
Olgastraße (north)	MT	702
Sigmaringer Straße	CL(d)	1 114
Waiblinger Straße (north)	CL(s)	876
Waiblinger Straße (south)	CL(s)	674
Waldburgstraße	CL(d) / MT	304
Zabergäustraße (west)	CL(s) / MT	989
Zabergäustraße (east)	CL(s)	1 846
Zeppelinstraße	CL(d) / MT	650

CL(d): Cycle lane dotted
CL(s): Cycle lane solid
MT: Mixed traffic
MV volume: Peak hour

For the selection of survey periods, the German guidelines for traffic surveys were followed. These give several possible combinations of periods. The choice depends on the survey location and the time of the peak hour on the road in question. Based on the selected measurement routes, the following survey periods were chosen (FGSV, 2012):

- 07:00 to 10:00 (hereafter: morning)
- 12:00 to 14:00 (hereafter: midday)
- 15:00 to 18:00 (hereafter: afternoon).

Surveys were carried out from September to November 2022. On each measurement route, each survey period was measured once. The three survey periods of each individual measurement route were not measured on a single day. Instead, the measurement trips for each rout were made on two to three different days. These days did not necessarily follow each other directly. However, by taking into account the specifications of German traffic survey guidelines, it can be assumed that regular traffic occurred on each survey day and that there were no relevant differences between the individual measurement trips.

The selected measurement routes were ridden continuously and alternately in both directions during the survey periods. With a selection of 14 measurement routes, this results in a total of 25 riding directions, as some routes could only be ridden on in one direction. This results in a gross riding time of eight hours per measurement route. A break of approximately ten minutes was scheduled, within each hour.

2.2 Definition of overtaking manoeuvres

When using the OpenBikeSensor, it is necessary to record the OMs that occur by pressing a button on the sensor's control panel shortly after each OM. This section explains which situations were recorded as OMs during the survey periods. §5 of Straßenverkehrsordnung (German road traffic regulations) demands vehicles to overtake on the left. Therefore, all MVs passing on the left side of the test person were recorded, with following exceptions:

- Oncoming vehicles, as the prescribed lateral distance does not apply in this case.
- Overtaking bicycles, as the prescribed lateral distance does not apply in this case.
- MVs passing on the right, as this case did not occur on the selected routes.
- Cycling in mixed traffic: Vehicles positioned on the left in a separate lane, as their driving

behaviour does not resemble traditional overtaking manoeuvres.
- Cycling on a cycle lane (dotted or solid): Vehicles in lanes that are not directly adjacent to the cycle lane, as their driving behaviour does not resemble traditional overtaking manoeuvres.

Cycle lanes with solid lines are legally not a part of the carriageway in Germany. Therefore, a MV driving past a bicycle which is on such a cycle lane is not considered overtaking. There is an ongoing discussion whether the prescribed lateral distance can be applied in these situations (Müller, 2018). Within this study, said situations were recorded as OMs, because it is expected that cyclists perceive them the same way as regular OMs.

2.3 Appearance and behaviour of the test person

The test person is a 36-year-old man with a height of 1.78 m. The following equipment and clothing was used during the test rides:

- Bicycle (a black Pedelec, compliant with German road traffic licensing regulations)
- Bicycle helmet (yellow)
- High visibility vest (yellow, without sleeves)
- Reflective bands, wrapped horizontally around the lower legs (yellow, 4 cm wide)
- Everyday clothing (rain coat, jeans, trainers—alternating colours)
- Backpack (black/grey).

Except for the changing colours of the clothing, each measurement trip was carried out with identical equipment. The lights on the bicycle were turned on all at all times.

A list of specifications for the test person's riding behaviour was drawn up before the start of the test rides. By reproducing these specifications on each measurement trip, the influence of the riding behaviour on the results should be as traceable as possible:

- **Speed.** An average speed of between 15 and 20 km/h was aimed for. This corresponds to the target speed for cycle routes within municipalities according to German guidelines (FGSV, 2010). The city of Stuttgart does not collect data on the actual speed of cyclists.
- **Distance to the edge of the carriageway (in mixed traffic).** For mixed traffic, a distance of 75 to 100 cm from the right-hand edge of the carriageway has been targeted. As there is no data on actual cyclist behaviour and no specifications in German road traffic regulations, these values are derived from court rulings (Peters, 2011).
- **Distance to the edge of the carriageway (on cycle lanes).** Observations show that cyclists generally ride in the middle of cycle lanes (Richter et al., 2019). This behaviour was targeted during the measurement trips.
- **Distance to parked vehicles.** According to court rulings, cyclists must behave in such a way that opening vehicle doors do not endanger them. The width of modern car doors varies between 0.80 m and 1.50 m (Peters, 2011). In order not to restrict the space for overtaking, a distance of between 1.00 m and 1.50 m was targeted. In case of cycle lanes parallel to longitudinal parking spaces, care was taken not to leave the cycle lane, while rather reducing the distance to parked vehicles.

2.4 Statistical analysis

For research question 1, the data from all the measurement routes are divided into three groups, one for each type of infrastructure. The three groups are analysed using a one-way analysis of variance (ANOVA). This procedure can be used to compare the means of several groups of samples with each other. The dependent variable used here is the lateral distance of the OMs. The independent variable is the type of cycling infrastructure. The same analysis is performed for the data concerning the time of day (research question 3). Lateral distance is chosen as the dependent variable and time of day as the independent variable. If the ANOVA confirms significant differences between multiple groups, multiple comparison analysis is performed post-hoc using the Tukey HSD test.

To analyse the influence of MV traffic volume on lateral distances (research question 2) a linear regression is performed. This tool can be used to identify the influence of an independent variable (in this case MV traffic volume) on a dependent variable (in this case the mean value of the lateral distances of each measurement route). If the linear regression result confirms a significant correlation, then the answer to research question 2 will be in the affirmative.

3 Evaluation

3.1 Overview

During the course of this study, 4 081 OMs were recorded on a total of 14 measurement routes. Figure 1 gives an overview of the lateral distances recorded.

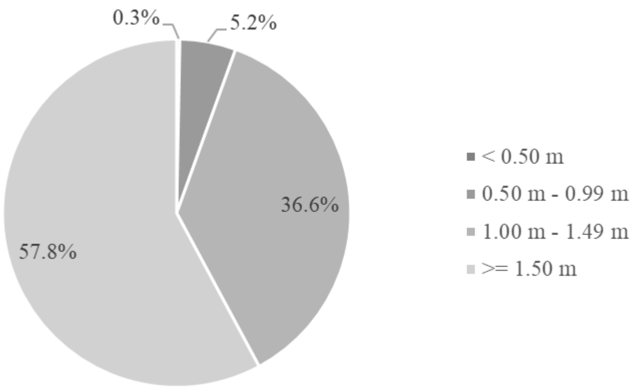

Figure 1 Overview on lateral distances

In total, 42.1% of all recorded OMs were performed with lateral distances below 1.50 m and were therefore too close. The mean value of all lateral distances is 1.59 m (SD = 0.40 m). The median value of all lateral distances is 1.57 m. The smallest recorded lateral distance is 0.24 m. There were OMs with a side distance of less than 1.00 m on all measurement routes.

The average speed of the test person over all the measurement routes was between 14.1 and 22.7 km/h. This means that in a few cases the self-imposed speed (15–20 km/h) was undershot or exceeded.

3.2 Influence of cycling infrastructure

This project considered measurement routes with three different types of cycling infrastructure. In order to investigate research question 1, the results of these three types of infrastructure are compared with each other. Table 2 shows a summary of the survey results.

Mean and median values of lateral distances are higher for routes with mixed traffic, than for routes with cycle lanes. A one-way ANOVA confirms that there is a statistically significant difference in lateral distances between at least two of the groups ($F(2, 4078) = 13.625$, $p < 0.0001$).

To investigate research question 1, the groups are compared post-hoc using the Tukey HSD test. The Tukey HSD test shows that the mean values (MV) of the lateral distances between the mixed traffic and cycle lane (dotted line) groups are significantly different (MV_{mixed} = 1.65 m, MV_{dotted} = 1.57 m; $p < 0.0001$, 95% C.I. = [0.043, 0.118]). There is also a significant difference between the mixed traffic group and the cycle lane (solid line) group (MV_{mixed} = 1.65 m, MV_{solid} = 1.58 m; $p < 0.0001$, 95% C.I. = [0.031, 0.111]). There is no significant difference between the mean values of the lateral distances of the cycle lanes (dotted line) group and the cycle lanes (solid line) group (MV_{dotted} = 1.57 m, MV_{solid} = 1.58 m; $p = 0.803$, 95% C.I. = [-0.025, 0.044]). Thus, it can be confirmed that cyclists on cycle lanes are overtaken more closely by MVs than cyclists in mixed traffic. The effect strength is $\eta^2 = 0.01$. The influence of the bicycle infrastructure on the lateral distances can therefore be classified as present, but small.

3.3 Influence of MV traffic volume

In order to investigate research question 2, the correlation between the MV traffic volume and the mean value of the lateral distances of each measurement route is analysed. Each point in the Figure 2 represents one riding direction on a measurement route.

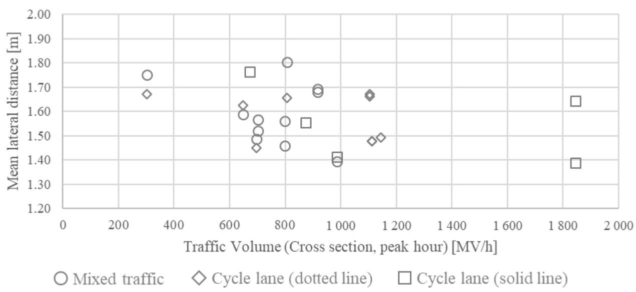

Figure 2 Correlation between traffic volume and mean lateral distance

Across all measured routes, there seems to be a slight tendency towards smaller lateral distances with increasing MV traffic volume. According to FGSV (2010), cycle lanes are more likely to be installed on roads with higher MV traffic volumes. Since, as shown, the type of infrastructure has an influence on the lateral distances, this could explain the trend described. However, other potential influencing factors, such as lane width or the presence of a guidance line in the middle of the lane, are ignored in this consideration and could also have an influence on the lateral distances that occur.

It is necessary to check whether there is a significant correlation between lateral distances and traffic volume. For this purpose, a linear regression was

Table 2 Results per cycling infrastructure

Infrastructure type	n	Mean value (SD)	Median value	OM < 1.50 m	OM < 1.00 m	OM < 0.50 m
Mixed traffic	980	1.65 m (0.42 m)	1.63 m	36.2%	5.0%	0.4%
Cycle lane (dotted line)	1 805	1.57 m (0.40 m)	1.54 m	45.1%	5.8%	0.4%
Cycle lane (solid line)	1 296	1.58 m (0.39 m)	1.56 m	42.7%	5.7%	0.2%
TOTAL	4 081	1.59 m	1.57 m	42.2%	5.6%	0.3%

performed. The linear regression shows that MV traffic volume has no significant influence on the mean value of the lateral distances ($R^2 = 0.108$, $F(1,23) = 2.971$, $p = 0.108$).

3.4 Influence of time of day

Table 3 compares the data from the survey periods in order to examine research question 3.

As expected, most OMs were recorded in the afternoon, as this is also the time when MV traffic volume is usually at its highest. More OMs were recorded in the morning than at midday. The morning survey period lasts three hours, whereas the midday survey period lasts two hours. Thus, on average approximately the same number of OMs were marked per hour in the morning and at midday.

There is only a slight difference between the median and mean values for the survey periods. In the afternoon there seem to be slightly more overtaking events below 1.50 m than at other times. To confirm this, a one-way ANOVA is performed. Lateral distance is chosen as the dependent variable and the survey period as the independent variable. The one-way ANOVA shows that there is no statistically significant difference between the lateral distances of the three survey periods ($F(2, 3153) = 0.973$, $p < 0.378$).

4 Discussion

This study aimed to analyse the lateral distances between bicycles and overtaking MVs, based on measurements in Stuttgart, Germany. 42.1% of the lateral distances measured were less than 1.50 m and therefore did not meet the requirements of the German road traffic regulations. All other studies analysed showed similar or higher values, ranging from 43% to 75% (Koppers et al., 2021; Langer, 2016; Merk et al., 2022; Plavec & Schmock, 2021; Richter et al., 2019; Tagesspiegel, n/d). Possible reasons for this difference are the routes chosen and the local characteristics. Riding style of the test persons could also be an explanation. In this project, the lateral distances were collected from a single test person. This made it possible to study variables without results being influenced by riding style. Projects that collect lateral distances from a large number of subjects can give a more balanced overall picture. The test person in this study chose an outwardly confident riding style. Whether cyclists with a different riding style are more likely to be closely overtaken remains to be seen in future research.

Research question 1 set out to analyse the effect of cycling infrastructure on lateral distances. Cyclists in mixed traffic experience higher mean and median values of lateral distances as well as a lower percentage of close OMs compared to cyclists in cycle lanes. Therefore, it can be said that cycle lanes lead to closer OMs than mixed traffic. These results are in line with the findings of other studies. The majority of existing research projects find higher lateral distances in mixed traffic than in cycle lanes (Merk et al., 2022).

Research question 2 aimed to analyse the influence of MV traffic volume on lateral distances. We could not confirm a relationship between those factors. Therefore, it cannot be concluded that cyclists are overtaken more closely on high traffic roads than on roads with fewer traffic. This has not been analysed in any other studies and can therefore be considered novel. The focus of German design guidelines on MV volume can therefore not be justified by a correlation with lateral distances. Although the proportion of close overtaking does not increase with MV traffic volume, high MV traffic volumes should still be seen as negative for cyclists. The higher the MV traffic volume of a road, the more OMs can be expected. This increases both the probability of accidents on the one hand and the subjective stress of cyclists on the other (Merk et al., 2021). The results of this work therefore do not imply that cycling traffic should be guided in mixed traffic at high traffic volumes without separation from MV traffic.

Table 3 Results per survey period

Period	n	Mean value (SD)	Median value	OM < 1.50 m	OM < 1.00 m	OM < 0.50 m
Morning (07:00–10:00)	1 081	1.62 m (0.42 m)	1.63 m	37.7%	5.6%	0.6%
Midday (12:00–14:00)	722	1.60 m (0.40 m)	1.62 m	36.7%	5.5%	0.3%
Afternoon (15:00–18:00)	1 353	1.59 m (0.42 m)	1.61 m	40.9%	6.9%	0.2%
TOTAL*	3 156	1.60 m	1.62 m	38.9%	6.2%	0.4%

* On two measurement routes construction sites were present during the morning periods, which could have influenced results. Thus, all measurements from both routes were excluded from this part of the analysis.

Research question 3 aimed to analyse the influence of time of day on lateral distances. With the available data we could not confirm an influence. It can therefore be assumed that the average lateral distance on a road is the same throughout the day. This is also a new finding. German design guidelines use the peak hour of MV traffic as input variable for the selection of bicycle infrastructure. According to the results, there is no need to question this, as lateral distances do not differ between the peak hour and other times.

The findings of this study have some limitations. All data was collected by a single test person on a few selected routes. This was done to ensure a high level of comparability between the routes analysed and to limit the influence of riding style on the results. On the other hand, this method does not give representative results for all cyclists. The use of more cyclists on selected routes could provide information on the influence of riding style and cyclist appearance on lateral distances. Analysing more routes would be expected to provide more detailed information on the influencing factors related to individual roads. The volume of cyclist traffic was not included in the analysis, as this data was not available. It would be expected that the volume of cyclists on a road could have a significant influence on lateral distances. This should be investigated in further research. Further research should also focus on road and bicycle infrastructure design. Variables such as carriageway and cycle lane width were not considered in this study and could provide deeper insights into the topic of lateral distances. In order to have a comprehensive view of the topic, it could also be helpful to look at the perspective of MV drivers. A psychological perspective could show which influences act on the behaviour of MV drivers (e.g. road environment, stress, personal attitudes), how this influences the execution of OMs and with which measures low lateral distances can be prevented.

5 Conclusion

In this study, we analysed lateral distances between MVs and cyclists during OMs. One test subject collected data from a total of 4 081 OMs in the city of Stuttgart, Germany. In total, about 42 % of the OMs were performed with a lateral distance of less than 1.50 m, which is the required lateral distance of German road traffic regulations. For further investigation, we addressed three research questions. First, we analysed the influence of bicycle infrastructure on lateral distances. We found that cyclists on cycle lanes were overtaken significantly closer, than cyclists in mixed traffic. Second, we analysed the influence of MV traffic on lateral distances. The data could not confirm a relationship between MV traffic and lateral distances. Third, we analysed the influence of time of day on lateral distances. A relationship between time of day and lateral distances could not be confirmed. The results provide valuable insights into the factors that influence lateral distances between MVs and cyclists and can be incorporated in the process of building safe cycling infrastructure and networks.

Overall, survey results indicate an urgent need for action. The fact that 42% of all OMs are carried out in contravention of traffic rules must be seen as negative for cyclists. Low lateral distances lead to a low level of subjective safety. Subjective safety is a crucial lever to strengthen cycling in the context of climate change. Using the knowledge gained through this analysis can be a first step in building safer cycling infrastructure. Further research on the influence of infrastructure design and cyclist behaviour can further facilitate cycling safety.

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CRediT contribution statement

Leo Casey: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing—original draft, Writing—review & editing. **Lutz Gaspers:** Methodology, Supervision. **Harald Mandel:** Methodology, Resources, Supervision.

Declaration of competing interests

The authors report no competing interests.

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