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Decentralized mobility hubs in urban residential neighborhoods improve the contribution of carsharing to sustainable mobility: findings from a quasi-experimental study

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Abstract

Carsharing contributes to sustainable urban mobility by reducing private car ownership and use. Thus, policy-makers and planners need to know how cities can foster carsharing and the related benefits. Decentralized mobility hubs are an emerging approach to supporting carsharing. These hubs provide designated carsharing parking spots in the public street spaces of urban residential neighborhoods. The objective is to embed carsharing services into the immediate residential environments of urban households. Thus, the hubs are intended to make carsharing more accessible, reliable, and convenient. However, there is a lack of empirical insights into the impact of decentralized mobility hubs on carsharing. This research uses survey data on carsharing users in the inner city of Hamburg, Germany, to appreciate the actual effects of such hubs on car ownership, transport mode usage, and the perception of carsharing. Decentralized mobility hubs have existed in several high-density residential neighborhoods in Hamburg since 2017. Our findings suggest that the use of these hubs leads to a substantially more positive perception of carsharing and, as a consequence, to a greater willingness of carsharing users to forgo car ownership. Ultimately, by supporting the reduction of private car ownership, the hubs promote not only carsharing, but also the use of other sustainable modes of transportation.

Keywords Car ownership · Car use · On-street parking · Street space allocation · Multimodality · Urban mobility

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Introduction

Space consumption by private cars is a serious challenge to urban transport planning (Newman et al. 2016). This is particularly true in the inner-city residential neighborhoods of major European cities, whose fundamental urban fabric was shaped before the automobile age (Jenks 2019). Due to high urban density and the low availability of off-street parking facilities, on-street parking is prevalent in these areas, which perpetually leads to pressure on the use of public street spaces. This problem is exacerbated by the fact that parked private cars constitute a highly inefficient use of space, as the average private car remains idle approximately 95% of the time (Shoup 2017). In addition to the issue of space consumption, high car ownership rates are also a source of concern from a sustainability perspective, since car ownership is an important variable in explaining car-oriented travel behavior (e.g., Dieleman et al. 2002; Ding et al. 2017; Schwanen et al. 2002; van Acker and Witlox 2010). Given these challenges, transportation researchers and planners need to find effective ways of reducing car ownership in urban settings.

In this context, carsharing is often considered a suitable way of decreasing the number of cars on the streets, while also increasing the use of sustainable modes of transportation. Several studies have found beneficial impacts of business-to-customer carsharing in a variety of European, North American, and Asian cities. According to these studies, carsharing services lead to reduced levels of private car ownership and a decrease in the number of trips and distances covered by private car use (e.g., Clewlow 2016; Jochem et al. 2020; Ko et al. 2019; Le Vine and Polak 2019). These changes are in turn associated with a greater use of public transit and non-motorized modes of travel (Kent 2014; Martin and Shaheen 2011b; Wittwer and Hubrich 2018), which ultimately reduces greenhouse gas emissions (Amatuni et al. 2020; Martin and Shaheen 2011a; Nijland and van Meerkerk 2017).

Mobility hubs have the potential to strengthen carsharing and further increase its contribution to sustainable urban mobility. Such hubs are recognizable places that offer and connect different transportation modes or mobility services (Anderson et al. 2017; Miramontes et al. 2017). The idea behind mobility hubs is to encourage and facilitate multimodal mobility as an alternative to car ownership and excessive car use. Carsharing is particularly relevant in the modal shift from private car use toward multimodal mobility patterns (Jonuschat et al. 2015; Nobis 2006), thereby making it a key element of mobility hubs.

Thus far, mobility hubs have mostly been realized in the vicinity of high-order public transportation. This usually limits them to a few central locations within a city. For the purpose of denser spatial coverage, major cities—such as Bremen and Hamburg in Germany—have started to establish mobility hubs in decentralized sites as well, for example in the minor streets of residential areas (Czarnetzki and Siek 2021; Glotz-Richter 2016; Muth 2018; Stein and Bauer 2019). These decentralized mobility hubs are typically characterized by a far smaller number and variety of mobility services and, unlike their central counterparts, are not necessarily linked to public transit.

Mobility hubs, particularly their decentralized variants, are still a young instrument of urban transport planning. Considering the diffusion of carsharing and other new mobility services, we expect that a growing number of cities will consider the adoption of such hubs. There is, however, little evidence on the effects of decentralized mobility hubs that has been gained from examining the hubs that have already been implemented. To provide planners and policy-makers who are interested in mobility hubs with a deeper understanding of this approach and its implications, our paper presents findings from a recent evaluation of decentralized mobility hubs in several inner-city residential neighborhoods

in Hamburg, Germany. We focus on the role of these hubs in changing the perceptions and impacts of carsharing, since the decentralized hubs in Hamburg are explicitly aimed at promoting carsharing as an alternative to car ownership. Accordingly, our paper is centered around the following research questions:

1. How does the use of decentralized mobility hubs influence the perceptions of carsharing among carsharing users?
2. How do these changed perceptions of carsharing in turn influence the impacts of carsharing on car ownership and transport mode usage?

The implementation of decentralized mobility hubs in Hamburg can be seen as a transport policy intervention that is targeted at changing the mobility behavior of carsharing users living in the vicinity of these hubs. Consequently, we used a quasi-experimental approach for our research in which we compared survey data on different groups of carsharing users, depending on whether and how they had been affected by decentralized mobility hubs.

Previous research

Carsharing and its contribution to sustainable mobility

Although the carsharing market is still a niche that is mainly confined to larger cities, business-to-customer carsharing services have become increasingly important in recent years, with rising membership numbers and growing fleet sizes, notably in Asia and Europe (Shaheen and Cohen 2020). Concurrently with this development, the last decade has seen a considerable increase in academic research on carsharing. Many of these contributions have addressed the question of whether carsharing is conducive to sustainable mobility. In principle, carsharing is a form of car use. On the other hand, in clear contrast to private car ownership, carsharing involves lower, or even no, fixed costs, but higher variable costs. Furthermore, awareness of the costs of carsharing usage is usually more pronounced, while the costs of running private cars are often underestimated by their owners (Andor et al. 2020). The pricing structure of carsharing, hence, encourages minimizing carsharing use and relying on other transportation modes as much as possible (Litman 2000). A number of studies have confirmed that carsharing does indeed lead to a reduction in the volume of car travel (e.g., Kent 2014; Liao et al. 2020; Nijland and van Meerkerk 2017). Although zero-car households gain auto access by joining carsharing and consequently increase their number of vehicle kilometers traveled, these changes are small compared to the decline in car travel in households that dispose of private cars or refrain from purchasing a car due to the availability of carsharing (Martin and Shaheen 2011a).

In general, both free-floating one-way (e.g., Jochem et al. 2020; Le Vine and Polak 2019) and station-based roundtrip carsharing (e.g., Ko et al. 2019) have been shown to help users either reduce or avoid car ownership. Nonetheless, station-based schemes are more likely to be perceived as suitable substitutes for private cars and, therefore, to exert a substantially stronger impact on car ownership (e.g., Becker et al. 2017; Giesel and Nobis 2016; Namazu and Dowlatabadi 2018). Glotz-Richter (2016) attributes this to the lower level of reliability, the limited operational areas, and the smaller range of available vehicle types and tariffs of free-floating schemes. The usage patterns of both types differ as

well. For instance, Becker et al. (2017) found that station-based roundtrip carsharing is mostly common for trips that actually require a car, while a main purpose of using free-floating carsharing is to save time compared to other modes. Therefore, of both schemes, free-floating carsharing is more commonly used as a substitute for public transit (Silvestri et al. 2021). However, Becker et al. (2018) and Rotaris et al. (2019) pointed out that this substitution mainly occurs when public transit is not an attractive alternative, such as in the late evening and night hours, or for longer intra-urban trips. In fact, many researchers see carsharing as an important complement, rather than a rival to public transit (e.g., Becker et al. 2018; Costain et al. 2012; Martin and Shaheen 2011b). Moreover, Ceccato and Diana (2021) and Rotaris et al. (2019) also noted that joining carsharing does not lead to a significant reduction in travel by walking or cycling, while Martin and Shaheen (2011b) even associated carsharing adoption with a more extensive use of non-motorized modes.

Research further shows that changes in car ownership and travel behavior supported by carsharing ultimately lead to a reduction in greenhouse gas emissions (e.g., Martin and Shaheen 2011a; Nijland and van Meerkerk 2017). Possible rebound effects resulting, for example, from different lifetimes of private cars and carsharing vehicles have not been considered in most calculations thus far. An exception is the paper by Amatuni et al. (2020), which demonstrated that even when including such rebound effects, carsharing still leads to a reduction in greenhouse gas emissions, albeit to a lesser extent.

In summary, most of the existing literature indicates beneficial impacts of carsharing on car ownership and mode usage. Of course, it must be kept in mind that the majority of those publications focus on individual cities or countries and are thus influenced by the respective cultural and geographic contexts. Furthermore, the previous contributions differ considerably in their methodological approaches. Some studies examine very specific groups, such as university students. In addition, certain findings are based only on stated preference methods, which involve a high level of abstraction. Observational studies that compare, for instance, the actual mobility behavior of carsharing users and non-users are prone to pitfalls, such as self-selection and simultaneity biases, together with reverse causality (Mishra et al. 2019). However, even taking these limitations into account, the current state of the research provides strong evidence that carsharing contributes to sustainable urban mobility.

Mobility hubs as support for carsharing

Mobility hubs are intended to promote multimodal mobility. Researchers have shown that the variability of mode choice influences the transition probabilities between different patterns of mobility behavior, which means that multi-mode users are, for example, more willing to substitute car use for public, or active, transportation (e.g., Heinen and Ogilvie 2016; Kroesen 2014).

Because of its impact on private car ownership and its strong association with multimodality (e.g., Jonuschat et al. 2015; Kopp et al. 2015; Nobis 2006), carsharing is a crucial component for the success of mobility hubs. In turn, the availability of carsharing vehicles and dedicated parking spaces at mobility hubs may support carsharing and its contribution to sustainable mobility. Many papers in recent years have highlighted the importance of exclusive parking spots for the effectiveness of carsharing, particularly in areas that experience shortages in parking space (e.g., Abbasi et al. 2021; Chen et al. 2018; De Luca and Di Pace 2015; Dowling and Kent 2015; Paundra et al. 2017). Moreover, carsharing can benefit from enhanced visibility and accessibility when combined with mobility hubs. Especially in

high-density inner city areas, many carsharing stations are currently located in unremarkable and limited-access locations (e.g., backyards, underground garages), which diminishes the attractiveness of these services (Chen et al. 2018; De Lorimier and El-Geneidy 2013; Loose and Nehrke 2019). Thus, conveniently accessible carsharing vehicles and parking spaces are pivotal to the impact of carsharing, as the vast majority of potential and actual carsharing users only accept distances up to a few hundred meters to the nearest vacant vehicle. Regarding free-floating carsharing, Herrmann et al. (2014) and Ampudia-Renuncio et al. (2018) consistently found that approximately 80% and 85% of users, respectively, were willing to undertake distances of no more than 500 m to the closest available vehicle, with approximately 20% and 30%, respectively, even renouncing carsharing if the distance exceeded 300 m. Similarly, in the study by Rotaris et al. (2019), a maximum access distance of 500 m was seen as critical to the acceptance of carsharing as a mobility option. Ko et al. (2019) discovered that users of a station-based carsharing service were particularly willing to either reduce or end their car ownership if they could reach the nearest station within 150 m or within three minutes from their home. Paundra et al. (2017) identified an access time of no more than five minutes as the threshold above which the attractiveness of carsharing compared to having one's own car strongly decreased. It can thus be drawn from previous research that mobility hubs must not be constrained to a few central locations if they aim to provide widespread support for carsharing.

Consequently, small, decentralized mobility hubs within residential neighborhoods form an emerging variant of mobility hubs (Glotz-Richter 2016; Muth 2018). In contrast to larger mobility hubs located at significant nodes of public transit corridors, smaller decentralized hubs usually have either no or only rudimentary connections to the public transit system. Their offering of mobility options is also more limited and can in fact consist only of carsharing services. This enables greater spatial coverage, thereby placing the mobility hubs even closer to the homes of urban residents (Czarnetzki and Siek 2021). Thus, unlike the usual intent of mobility hubs, decentralized hubs are primarily targeted at the start or end of a trip rather than at the seamless interchanges between transport modes during a trip.

However, there is a critical research gap regarding the impact of mobility hubs on new mobility services such as carsharing. Moreover, research on mobility hubs to date has mainly focused on the conceptual level of their deployment. Anderson et al. (2017), for instance, developed a methodology for determining optimal hub locations and applied it to a case study in Oakland, California. Tran and Draeger (2021) created an evaluation framework to assess the sustainability and equity impacts of hub implementation strategies under different scenarios in the North American cities of Portland, Seattle, and Vancouver. Beyond that, empirical studies concerning actually implemented mobility hubs are even rarer. However, the paper by Miramontes et al. (2017) deserves special mention here. The paper is based on the evaluation of a large mobility hub at a major subway and streetcar station in the inner city of Munich, Germany. Among the key findings is that the mobility hub effectively leads to the promotion of carsharing and multimodal mobility patterns. Another is that the users of this hub wish to have additional, smaller hubs in residential areas. To the best of our knowledge, the effects of such decentralized mobility hubs in urban residential neighborhoods have thus far not been explored in the English-language literature.

Methods and data

In November 2017, the city of Hamburg launched a large-scale program for the implementation of decentralized mobility hubs—officially labeled hvv¹ switch stations—in the inner city. The decentralized hubs complement the larger central mobility hubs that have been established in Hamburg since 2013 and now exist at 18 commuter rail and subway stations.² By providing carsharing vehicles and exclusive parking spaces via decentralized mobility hubs in the immediate residential environments of urban households, carsharing was expected to become more reliable and convenient. This provision was intended to make it easier for residents to forgo their private cars and thus ultimately foster not only carsharing but also public and active modes of transportation. To assess the impact of this approach, the implementation of decentralized hubs was accompanied by our evaluation study in 2019 and 2020. We defined our research as quasi-experimental since we examined an intervention, while the circumstances surrounding that intervention were determined by other factors outside of our study (Leatherdale 2019). To allow for causal inferences, we conducted surveys in inner-city residential neighborhoods, both with and without decentralized mobility hubs. The target group of these surveys was active carsharing users.³ Our aim was to create similar subsamples that differed significantly only in terms of whether and how these carsharing users had been affected by the mobility hubs. We defined users of mobility hubs living in the vicinity of these facilities as the intervention group (i.e., they had been exposed to and thus influenced by the intervention), while participants from neighborhoods without mobility hubs formed the control group. Hamburger Hochbahn AG, which is the city's largest public transit operator, commissioned the research. However, because the evaluation was commissioned only after the hubs had been implemented, our data collection was limited to the post-intervention phase.

Study sites

Approximately 50 decentralized mobility hubs existed during our research. Although their offerings were limited to carsharing, they were considered hubs since they combined different carsharing services and types. Carsharing vehicles supplied by Share Now (free-floating one-way carsharing) or Cambio CarSharing (station-based roundtrip carsharing) were permitted at the hubs. Each location had three to four dedicated carsharing parking spots that were created by converting ordinary on-street parking spaces to embed the hubs directly into the street space (Fig. 1). All carsharing operators who were authorized at the mobility hubs shared the same parking spaces, meaning there were no designated spots for

¹ The abbreviation “hvv” stands for Hamburger Verkehrsverbund, which is an association that coordinates public transit in the Hamburg metropolitan area.

² The mobility hubs are part of Hamburg's multimodal mobility concept named hvv switch, which has the objective of integrating new shared mobility services with public transit. Alongside the mobility hubs, the concept of hvv switch also includes a mobility application (hvv switch app) that allows travelers to plan, book, and pay for the use of various mobility services in Hamburg in a simple way. In the background, a digital mobility platform organizes the linkage of app-based mobility services (e.g., carsharing, on-demand ride-pooling) with physical infrastructure (e.g., mobility hubs featuring parking lot sensors).

³ Prior to the surveys, we conducted 21 qualitative, semi-structured face-to-face interviews with residents living near decentralized mobility hubs in April and May 2019. Both users and non-users of carsharing services and mobility hubs were interviewed. The findings from this qualitative approach helped in the development of the surveys but are not presented in this paper.



Fig. 1 Decentralized mobility hub in the inner-city neighborhood of Ottensen, Hamburg (Source: Authors)

individual companies. Trips using vehicles from the station-based service were required to end at the hub where they started. However, cars from the free-floating service were not bound to any hub. Street signs, as well as slabs on the surface of the parking spaces, ensured that the hubs were recognizable.

In preparation for the survey of the intervention group, 16 decentralized mobility hubs were randomly selected as the starting points for determining the intervention areas to be studied. As the number of mobility hubs in Hamburg has been growing continuously since 2017, only those hubs that had already been in existence for at least six months at the beginning of the survey were taken into account in the sampling. The average age of the selected hubs at the time the survey was launched was approximately 13 months. In this way, we wanted to give the residents enough time to have experiences with the new mobility options and to possibly make changes in terms of their travel behavior and car ownership status.

Using spatial network analysis in a geographic information system, we then identified all the residential addresses within a maximum walking distance of 400 m from the mobility hub at each of the 16 selected locations. The outer boundaries of the accessibility polygons created in the network analysis partially intersected city blocks and street segments. This made it difficult for us to calculate the number of addressable households, since we only had household data at the block level. Therefore, we eventually adjusted the accessibility polygons to the nearest city block boundaries to shape the final study areas of the intervention arm (Fig. 2).

The next step was to identify appropriate study sites for the survey of the control group. Due to the lack of random assignment of participants to subsample groups, baseline differences between intervention and control groups can lead to severe bias in quasi-experimental studies (Craig et al. 2012). Consequently, we safeguarded the comparability of the groups via an area-based matching approach. We first analyzed the 16 previously

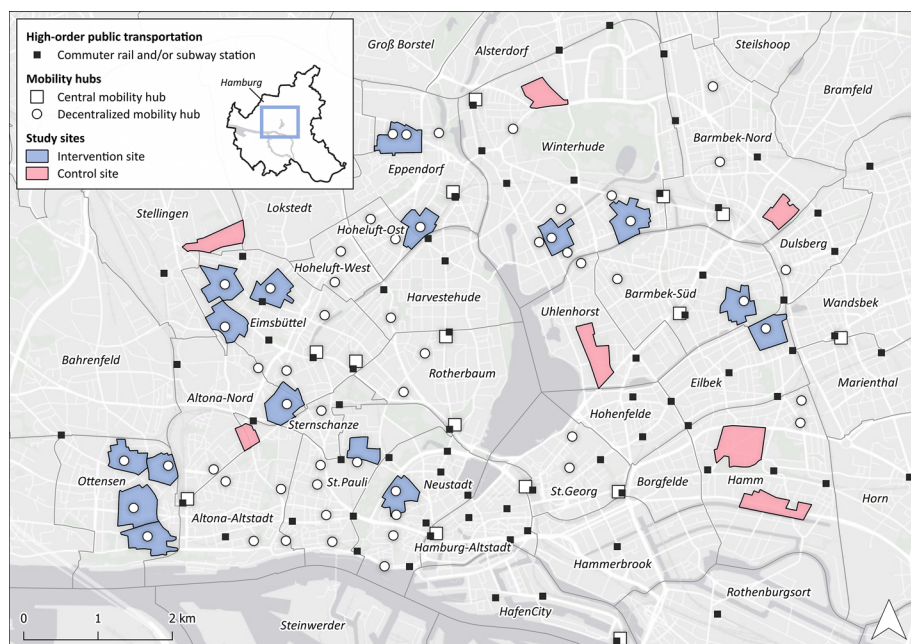


Fig. 2 Map of the inner city of Hamburg, showing the locations of mobility hubs (as of November 2019) and study sites (Visualization: Authors; Basemap: ESRI, OpenStreetMap and contributors)

determined study sites for the intervention arm at the city block level using several variables, including land use, urban density, demographic structure, socioeconomic status, public transit accessibility, and availability of carsharing services. Subsequently, we identified seven clusters of city blocks that resembled the selected intervention areas in the central districts of Hamburg, except for the existence of mobility hubs in or near the neighborhoods. None of these seven control sites were located closer than 500 m to a mobility hub, with the largest parts of the areas even being considerably further away from the nearest hub. This process was undertaken to prevent the control group from being contaminated by any influence of the intervention.

Data acquisition

The survey phase began in November 2019 and ended in February 2020. A postcard was sent to every contactable household within the 23 selected neighborhoods, which provided a brief description of the research project and an invitation to take part in the survey. The postcard was addressed to a randomly selected adult in each household. Approximately 17,300 households were reached in the intervention arm, and a further 6100 households were reached in the control arm of our study. As the data collection itself was conducted through a web survey, each postcard contained a short URL, as well as a QR code, which redirected the respondent to the online questionnaire. We administered the web survey ourselves. A lottery was used as an incentive to participate, but only those persons who completed the questionnaire were eligible. Ten cash prizes in the amount of 100 EUR each were raffled off to participants. We chose this relatively small prize to minimize the risk

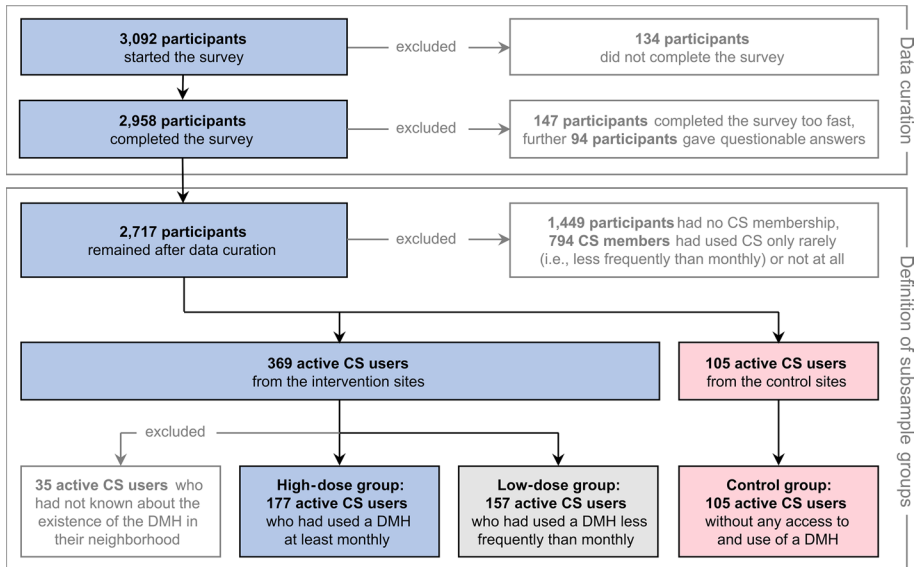


Fig. 3 Procedure of data curation and definition of subsample groups. *CS* carsharing, *DMH* decentralized mobility hub

that people with no interest in the survey topic would participate solely because of the possible prize. It was also possible to fill out the questionnaire without participating in the lottery.

In addition to obligatory questions on the sociodemographics of the respondents, the web survey included questions regarding car ownership, carsharing membership, and the perception and use of certain transport modes. If participants reported that they were familiar with using carsharing and a mobility hub, they were given further questions on these topics. Moreover, the respondents in the intervention areas were shown a map at the end of the questionnaire, which displayed their respective neighborhoods and the location of the mobility hub. In these maps, the neighborhoods were divided into four zones, representing distances to the mobility hub in 100-m intervals. Respondents were then asked to specify in which zone they lived. This allowed them to tell us the approximated distance from their home to the mobility hub without having to reveal their exact address.

Data curation and definition of subsample groups

We visualized the data curation procedure in Fig. 3. Out of a total of approximately 23,400 persons contacted, 3092 respondents (13.2%) accessed the online questionnaire. Respondents who did not complete the survey were excluded from further analysis. We also excluded all participants who completed the survey too fast (i.e., completion time was below the fifth percentile), as well as all cases with plausible completion times yet questionable or contradictory responses. This led to an adjusted sample of 2717 respondents, of whom 2003 belonged to the intervention arm and 714 to the control arm. The response rate after data cleaning amounted to 11.6% and was thus at a satisfactory level, with the

response rates at the intervention sites (11.5%) and the control sites (11.7%) being almost identical.

The subjects who passed the data curation process up to this point represented a general sample of the population in the areas studied. Most of them were respondents without a carsharing membership and, therefore, were not relevant for the research questions of this study. As a consequence, from both the intervention and the control arms, we extracted all 474 carsharing members who reported using carsharing at least once a month. The idea behind this distinction, as supported by the existing literature (e.g., Ko et al. 2019), was that monthly use is the threshold of active carsharing usage, and an appreciable impact of carsharing on car ownership and mobility behavior is less likely with less frequent use.

We then sorted the active carsharing users into subsample groups based on their level of exposure to decentralized mobility hubs. In quasi-experimental studies, determining the exposure of subjects to an intervention is a critical challenge (Humphrey et al. 2016). We chose a straightforward method and defined exposure as the self-reported use of the mobility hub in the respective neighborhood. In this context, use means that a carsharing trip started or ended in the dedicated parking spaces of a hub.

Unsurprisingly, all 105 active carsharing users from the control sites stated that they had no experience using a decentralized mobility hub. They were therefore suitable to form the control group. However, the identification of subjects who had been exposed to the hubs was more complex. Of the 369 active carsharing users surveyed at the intervention sites, 35 respondents stated that they were not aware of and therefore had not used a decentralized mobility hub in their neighborhood. Nonetheless, it is possible that there was an indirect influence of the hub on these individuals. Since we were ultimately unable to reliably assess the level of exposure for these 35 respondents, they were excluded from the analysis. The remaining 334 participants in the intervention arm were then divided into two intervention subgroups, depending on how frequently they had used the mobility hub. According to our definition of exposure, respondents with a more frequent use had received a higher dose of the intervention. Similar to the previous identification of active carsharing users, we again set the threshold at monthly usage. A total of 177 respondents had used the mobility hub at least once a month and thus represented the high-dose group, while 157 participants with less frequent use were assigned to the low-dose group. We formed two intervention groups instead of one, because we primarily hypothesized that the frequent and regular use of a hub will lead to changes in mobility behavior and in the perception of carsharing. To examine this hypothesis closely, we separated regular users from occasional users.

Statistical analysis

As a result of the data curation and the definition of subsample groups above, three groups of inner city residents were identified, who used carsharing frequently but differed greatly in regard to their access to a mobility hub in their neighborhood and their actual use. By means of descriptive-statistical methods and statistical hypothesis testing, we examined these groups for significant differences in car ownership, mode usage, and attitudes toward carsharing that can be inferred from exposure to decentralized mobility hubs. Concerning potentially confounding effects, the groups were also compared with regard to sociodemographic characteristics, as well as the number and types of carsharing services used. For the same reason, we investigated whether the groups differed considerably in their basic attitudes toward common modes of transportation. The comparison of these attitudes

was preceded by an exploratory factor analysis, which we will cover in more detail in the respective part of the results section.

Statistical analysis was performed in R 3.6. Chi-square tests were used to assess nominal and ordinal data. To compare the metric data of all three groups, we used one-way analyses of variance (ANOVAs) or, if a non-parametric method was needed, Kruskal–Wallis H tests. Pairwise comparisons of metric data were performed with independent samples t -tests or with non-parametric Mann–Whitney U tests, when appropriate. In the case of post-hoc tests with multiple comparisons, the Bonferroni–Holm method was used to adjust p -values (referred to as p_{adj} in the results section). We considered p -values below 0.05 to be statistically significant. Moreover, we calculated effect sizes and interpreted them following the recommendations of Cohen (1992).

A small fraction of the survey participants had missing data for one or more variables. The share of missing answers was highest for the question on income (7.1%). We used multiple imputation by chained equations (MICE; van Buuren and Groothuis-Oudshoorn 2011) to replace the missing data with estimated values based on other available data.

Representativeness of the subsample groups

Once our subsample groups were defined, we investigated their representativeness based on their sociodemographic characteristics. The literature shows that carsharing users differ substantially from the general population in terms of gender, age, educational attainment, and income, for example (e.g., Becker et al. 2017; Ceccato and Diana 2021; Giesel and Nobis 2016; Kopp et al. 2015; Prieto et al. 2017; Wittwer and Hubrich 2018). Therefore, instead of relying on census data, we used more specific data from the 2017 wave of the German National Household Travel Survey “Mobilität in Deutschland – MiD” as reference data of the population (Follmer et al. 2020; Nobis and Kuhnimhof 2018). Similar to our subsample groups, we limited the reference data to active carsharing users (i.e., at least monthly use) who lived in the inner city of Hamburg ($n=235$). In addition, we tested for statistically significant differences between the subsample groups that could have proven problematic for further analysis.

Table 1 depicts the sociodemographic characteristics of the subsample groups, as well as the reference distribution from the German National Household Travel Survey. Essentially, all three subsamples matched the expected profiles of carsharing users. The subsamples were typified by predominant proportions of men, young or middle-aged persons, one-or-two-person households, and households without children. Likewise, the high percentages of respondents with university degrees, full-time or part-time occupations, and higher socioeconomic status in all three groups were consistent with known findings. It is noteworthy, however, that the high-dose intervention group had the highest proportions of women, respondents from larger households consisting of at least three people, respondents from households with children, and people without current salaried employment (e.g., due to parental leave, full-time homemaking, retirement). These are characteristics that, according to the current state of research, have been comparatively rare among carsharing users to date. Nonetheless, the differences between the subsample groups were small and did not reach statistical significance. On the other hand, all three groups were very similar considering age, educational levels, and socioeconomic status. In summary, the sociodemographics of the three subsample groups did not lead to fundamental distortions in our further data analysis. We also found that the subsamples were representative of active

Table 1 Comparison of subsamples with each other and with reference data from the German National Household Travel Survey (NHTS) Mobilität in Deutschland—MiD

	Subsample groups			Chi-square test of independence	Population German NHTS MiD 2017
	Control (n = 105)	Low-dose (n = 157)	High-dose (n = 177)		
Gender					
Female	40.0 (42)	43.9 (69)	48.6 (86)	$\chi^2(2) = 2.05$	32.8 (77)
Male	60.0 (63)	56.1 (88)	51.4 (91)	$p = 0.359$ <i>Cramér's V</i> = 0.07	67.2 (158)
Age					
18–29 years	19.0 (20)	17.2 (27)	19.8 (35)	$\chi^2(6) = 4.36$	18.7 (44)
30–44 years	44.8 (47)	36.9 (58)	42.4 (75)	$p = 0.628$	51.5 (121)
45–64 years	34.3 (36)	41.4 (65)	35.6 (63)	<i>Cramér's V</i> = 0.07	27.2 (64)
≥ 65 years	1.9 (2)	4.5 (7)	2.2 (4)		2.6 (6)
Household size					
1 person	37.1 (39)	35.0 (55)	33.9 (60)	$\chi^2(4) = 1.61$	29.4 (69)
2 persons	40.0 (42)	40.8 (64)	37.3 (66)	$p = 0.807$	48.9 (115)
≥ 3 persons	22.9 (24)	24.2 (38)	28.8 (51)	<i>Cramér's V</i> = 0.04	21.7 (51)
Household with child(ren)					
Yes	21.9 (23)	26.1 (41)	28.8 (51)	$\chi^2(2) = 1.63$	19.6 (46)
No	78.1 (82)	73.9 (116)	71.2 (126)	$p = 0.443$ <i>Cramér's V</i> = 0.06	80.4 (189)
University degree					
Yes	79.0 (83)	79.6 (125)	75.1 (133)	$\chi^2(2) = 1.11$	71.5 (168)
No	21.0 (22)	20.4 (32)	24.9 (44)	$p = 0.574$ <i>Cramér's V</i> = 0.05	28.5 (67)

Table 1 (continued)

	Subsample groups		High-dose (n=177)	Chi-square test of independence	Population German NHTS Mid 2017
	Control (n=105)	Low-dose (n=157)			
Occupational status					
Full-time employed	81.9 (86)	80.9 (127)	74.6 (132)	$\chi^2(4)=5.13$	80.4 (189)
Part-time employed	12.4 (13)	8.9 (14)	12.4 (22)	$p=0.275$	8.5 (20)
Other status	5.7 (6)	10.2 (16)	13.0 (23)	<i>Cramér's V</i> =0.08	11.1 (26)
Socioeconomic status					
Low or very low	8.6 (9)	5.7 (9)	10.7 (19)	$\chi^2(6)=4.92$	4.2 (10)
Medium	20.0 (21)	24.2 (38)	20.9 (37)	$p=0.554$	30.2 (71)
High	40.9 (43)	36.3 (57)	41.3 (73)	<i>Cramér's V</i> =0.08	41.3 (97)
Very high	30.5 (32)	33.8 (53)	27.1 (48)		24.3 (57)

The population here is defined as active carsharing users living in inner-city areas of Hamburg. Percentages are shown, with absolute numbers of respondents in brackets

carsharing users in inner-city areas, as the distributions of sociodemographic characteristics—despite some differences in exact percentages—corresponded to the patterns of the population data.

Results

In the Methods and Data section, we have shown that there were no significant differences between the subsample groups in terms of sociodemographics. The first two paragraphs of the Results section focus on the basic mobility-related attitudes of the respondents and the carsharing services they used. In this way, we further investigate whether there were other crucial differences between the groups, besides exposure to decentralized mobility hubs, which could complicate inferences about the impact of the intervention. We then proceed to the key aspects of our study and examine car ownership, mode usage, and attitudes toward carsharing, since our research is grounded in the hypothesis that these variables, in particular, were influenced by the intervention. In the concluding part of this section, we compare the frequent and occasional users of mobility hubs (i.e., high-dose and low-dose intervention groups) on their perceptions of these facilities.

Attitudes toward transportation modes

Attitudes and norms can greatly influence mobility behavior. Therefore, we measured these attitudes through a set of psychometric questions (Table 2). The statements referred both to the perception of certain modes of transportation, such as the private car or public transit, and to more general beliefs and needs, such as the perceived importance of environmentally friendly mobility or the necessity of having a particular flexibility in one's everyday life. In compiling the statements, we were guided by existing papers (Beirão and Cabral 2007; Hunecke et al. 2010; Magdolen et al. 2019; Steg 2005; von Behren et al. 2018). We also incorporated insights from the 21 qualitative interviews that we conducted in preparation for the survey. Attitudes toward carsharing and mobility hubs are not included here, as they are considered separately in the Results section.

To reduce the complexity of the data and identify the underlying psychological motives of the responses, we subjected the 19 items to an exploratory factor analysis (Table 3), after examining the suitability of the data for this approach (Bartlett's test for sphericity: $p < 0.001$; Kaiser–Meyer–Olkin criterion: 0.81). A parallel analysis scree plot suggested a set of four factors. We rotated these factors using the direct oblimin method, since we expected the retained factors to be correlated with each other. Two items were omitted due to low factor loadings. Using Cronbach's alpha, we found the internal consistency of all factors to be sufficient according to the criteria of Nunnally (1978).

Factor 1 (affective-symbolic car use, $\alpha = 0.84$) describes how closely respondents associate the use of a car with fun, social status, freedom, and safety. Higher scores on this factor are also accompanied by a lower perceived importance of environmentally friendly mobility. In contrast, Factor 2 (instrumental car use, $\alpha = 0.75$) represents the use of a car as a means by which to address specific mobility needs that arise, for instance, from occupational or family demands. High scores on Factor 3 (public transit appreciation, $\alpha = 0.69$) signify individuals who can manage their daily lives well using public transit and are less affected by possible disadvantages of this mode, such as limited privacy, or at least feel less disturbed by it. Factor 4 (active transport enthusiasm, $\alpha = 0.72$), for its part, reflects

Table 2 Attitudes toward transportation modes

Item	Statement	Control group (n = 105)		Low-dose group (n = 157)		High-dose group (n = 177)		ANOVA <i>p</i>
		<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	
1	A car is just a means to an end for me	3.59	1.35	3.69	1.48	3.75	1.17	0.618
2	Driving a car is fun for me	3.49	1.38	3.35	1.42	3.28	1.17	0.436
3	Using a car means freedom for me	3.17	1.52	3.05	1.50	2.83	1.38	0.125
4	It is important to me what brand of car I am traveling with	2.03	1.14	1.95	1.26	1.81	1.10	0.273
5	In a car I feel safe and protected	3.23	1.25	3.16	1.22	3.03	1.18	0.366
6	It is important to me to use environmentally friendly transport modes	3.78	1.14	3.79	1.09	3.92	0.92	0.440
7	I often have to transport heavy or bulky items	2.18	1.31	2.06	1.20	2.19	1.18	0.559
8	I often have to travel to the outskirts or out of the city	2.81	1.46	2.91	1.25	2.55	1.26	0.042
9	In my everyday life, I have to be very flexible and mobile	3.35	1.30	3.42	1.20	3.37	1.17	0.893
10	I have to use a car for occupational reasons	2.02	1.45	2.09	1.50	1.86	1.39	0.350
11	I have to use a car for duties of my private life	2.11	1.30	2.08	1.34	2.02	1.27	0.832
12	I can easily reach what I need by public transit	3.30	1.22	3.18	1.14	3.23	0.99	0.701
13	I often feel disturbed by other people on public transit	2.80	1.30	2.83	1.28	2.70	1.31	0.596
14	While on public transit, I use my travel time for other things	3.55	1.27	3.62	1.37	3.58	1.22	0.915
15	I like cycling because I enjoy the exercise	3.84	1.12	3.79	1.32	4.03	1.16	0.169
16	I ride a bicycle even in wet and cold weather	2.58	1.50	2.66	1.39	2.94	1.48	0.075
17	I like to walk even longer distances	3.40	1.21	3.49	1.25	3.56	1.05	0.538
18	I have to use a car for my leisure activities	2.74	1.34	2.69	1.32	2.65	1.25	0.842
19	I like to try out new mobility options	4.11	0.98	4.08	0.95	3.99	0.99	0.583

The table shows the mean level of agreement (*M*) and the standard deviation (*SD*) for each statement by subsample group. Agreement was measured on a Likert scale ranging from 1 to 5 (i.e., from “strongly disagree” to “strongly agree”)

Table 3 Rotated factors and factor loadings of attitudes toward transportation modes

Item	Statement	Factor 1 Affective-symbolic car use	Factor 2 Instrumental car use	Factor 3 Public transit appreciation	Factor 4 Active transport enthusiasm
1	A car is just a means to an end for me	-0.82	0.02	-0.07	0.00
2	Driving a car is fun for me	0.80	-0.02	0.00	0.04
3	Using a car means freedom for me	0.70	0.05	-0.16	0.01
4	It is important to me what brand of car I am traveling in	0.54	0.14	0.09	-0.13
5	I feel safe and protected in a car	0.52	0.02	-0.31	-0.01
6	It is important to me to use environmentally friendly transport modes	-0.45	0.01	0.14	0.19
7	I often have to transport heavy or bulky items	-0.18	0.65	-0.30	0.05
8	I often have to travel to the outskirts or out of the city	0.02	0.62	0.02	0.01
9	In my everyday life, I have to be very flexible and mobile	0.02	0.62	0.22	-0.03
10	I have to use a car for occupational reasons	0.13	0.59	-0.01	0.00
11	I have to use a car for duties related to my private life	0.25	0.55	-0.03	-0.05
12	I can easily reach what I need by public transit	-0.03	-0.21	0.66	0.05
13	I often feel disturbed by other people on public transit	0.18	-0.16	-0.58	-0.11
14	While on public transit, I use my travel time to do other things	-0.03	0.01	0.58	-0.02
15	I like cycling because I enjoy the exercise	0.06	0.03	0.00	0.98
16	I ride a bicycle even in wet and cold weather	-0.23	-0.14	-0.04	0.56
17	I like to walk even longer distances	-0.07	0.03	0.15	0.46
18	I have to use a car for my leisure activities				
19	I like to try out new mobility options				
		Items omitted due to low factor loadings (absolute values < 0.40 for all factors)			

High factor loadings (absolute values > 0.40) are bolded. The values shown are the final factor loadings after omitting Items 18 and 19

the rather intrinsic motivation for using non-motorized modes, which remains in effect even under unfavorable circumstances (e.g., bad weather). Based on these four factors, we subsequently tested whether the subsample groups differed substantially in regard to their prevalent attitudes.

The three groups were highly similar in instrumental car use ($F(2, 436)=0.38$, $p=0.684$, $\eta^2<0.01$) and public transit appreciation ($F(2, 436)=0.04$, $p=0.952$, $\eta^2<0.01$). Conversely, similarity was lower for affective-symbolic car use ($F(2, 436)=1.78$, $p=0.170$, $\eta^2<0.01$) and active transportation enthusiasm ($F(2, 436)=2.07$, $p=0.127$, $\eta^2<0.01$), despite the threshold of statistical significance not being met. The lower p -values of the latter two tests were mainly caused by the fact that the agreement of the high-dose group with the statement, “Using a car means freedom for me,” was significantly lower, and at the same time, two statements on cycling (“I like cycling because I enjoy the exercise,” and “I ride a bicycle even in wet and cold weather”) applied to a noticeably greater extent in this group (Table 2). Although these findings must be considered in the interpretation of our further results, we nevertheless do not assume that the groups had substantially different attitudes toward transportation modes, given the strong similarities in the ratings of all other statements.

Number and types of carsharing services used

Giesel and Nobis (2016) and Jochem et al. (2020) showed that the impact of carsharing increases with the number of carsharing services used. In this context, the combined use of free-floating and station-based carsharing has been associated in previous publications with a particularly pronounced willingness to forgo car ownership (Giesel and Nobis 2016; Namazu and Dowlatabadi 2018). For our research, differences in the number and types of carsharing services used were a potential source of bias. We, therefore, examined the subsample groups using these variables as well. We included all carsharing services that respondents mentioned as being used, even if only seldom (i.e., < 1 time per month). Memberships without the actual use of the corresponding service were hence not taken into account.

The results are shown in Table 4. Once again, the groups were found to be very similar. The proportions of people who used only one service or only station-based schemes were slightly higher in the two intervention groups but did not lead to statistically significant differences. In each of the three subsample groups, more than 70% of the respondents exclusively used free-floating carsharing. At least in the high-dose group, this was not necessarily to be expected, as both free-floating one-way and station-based roundtrip carsharing were available at the mobility hubs. In this respect, we concluded that there was no material bias in the data of our subsample groups with regard to the carsharing services used.

Car-free and car-owning households

As a central hypothesis of our research, we assumed that car ownership of carsharing users was influenced by their use of decentralized mobility hubs. Figure 4 shows that the proportions of households owning zero, one, or even two private cars, indeed varied between the subsample groups. With a share of 57%, frequent users of mobility hubs were considerably more likely not to own a car than were respondents in the low-dose group and the control group (43% and 40%, respectively). There was a

Table 4 Number and types of carsharing services used by subsample group

	Control (n = 105)	Low-dose (n = 157)	High-dose (n = 177)	Chi-square test of independence
Number of CS services used				
1 service	14.3 (15)	21.0 (33)	22.0 (39)	$\chi^2(4) = 2.79$
2 services	53.3 (56)	47.8 (75)	47.5 (84)	$p = 0.594$
≥ 3 services	32.4 (34)	31.2 (49)	30.5 (54)	$Cramér's V = 0.06$
Types of CS services used				
One-way FFCS only	75.2 (79)	73.3 (115)	71.7 (127)	$\chi^2(4) = 5.09$
Roundtrip SBFS only	1.9 (2)	7.0 (11)	8.5 (15)	$p = 0.278$
Both types	22.9 (24)	19.7 (31)	19.8 (35)	$Cramér's V = 0.08$

Percentages are shown, with absolute numbers of respondents in brackets

FFCS free-floating carsharing, SBFS station-based carsharing

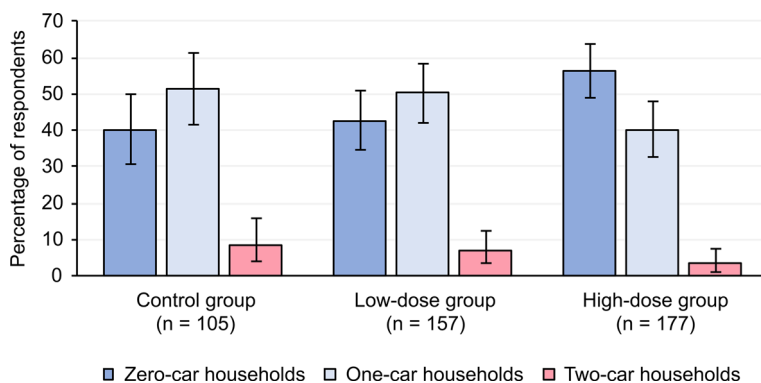


Fig. 4 Proportions of car-free and car-owning households by subsample group. Error bars indicate 95% confidence intervals

statistically significant relationship between the usage frequency of a mobility hub and the percentages of car-free and car-owning households ($\chi^2(4) = 11.08$, $p = 0.026$, $Cramér's V = 0.11$).

Consequently, households belonging to the high-dose group owned on average 0.47 (95% CI ± 0.08) private cars, while respondents in the low-dose group and the control group reported owning 0.64 (95% CI ± 0.10) and 0.69 (95% CI ± 0.12) cars per household, respectively. The differences regarding the number of cars per household were statistically significant ($H(2) = 10.79$, $p = 0.005$, $\eta^2 = 0.02$). Subsequent pairwise comparisons revealed that the high-dose group differed significantly from the low-dose group ($z = -2.66$, $p_{adj} = 0.016$, $r = 0.15$) and the control group ($z = -2.88$, $p_{adj} = 0.012$, $r = 0.17$), while the two groups with low or without exposure to the intervention showed no statistically significant deviations from each other ($z = -0.52$, $p_{adj} = 0.604$, $r = 0.03$).

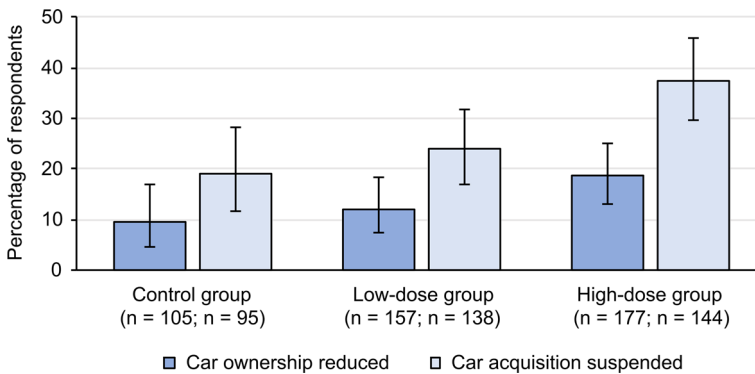


Fig. 5 Proportions of households that had reduced car ownership or had suspended car acquisition (reference period: 2018 and 2019) by subsample group. Households that had disposed of a car were not surveyed about suspended car acquisition, resulting in two sample sizes for each subsample group. Error bars indicate 95% confidence intervals

Decisions made against car ownership

Besides the car ownership at the time of the survey, we further investigated whether the participating households had disposed of a private car or suspended the purchase of such a car in 2018 and 2019. We limited the period considered to the last two years before the survey, in view of the still young age of the decentralized mobility hubs. To avoid redundancy, the respondents who reported that they had disposed of a car were not asked about car purchase avoidance.

Figure 5 illustrates the shares of households that had disposed of a car or deliberately avoided acquiring one. Again, the high-dose group clearly stood out. Compared to the control group, the frequent hub users were approximately twice as likely to have disposed of a car (19% vs. 10%) or to have refrained from car acquisition (38% vs. 19%). In contrast, the shares in the low-dose group were only negligibly higher than those in the control group in terms of car disposal (12% vs. 10%) and avoidance of car purchase (24% vs. 19%). The relationship between the usage of a mobility hub and deliberate decisions against car acquisition was found to be statistically significant ($\chi^2(2) = 11.48$, $p = 0.003$, *Cramér's V* = 0.17). On the other hand, when considering the association of mobility hub usage and car disposal, statistical significance was narrowly missed ($\chi^2(2) = 5.34$, $p = 0.069$). Nevertheless, we found a small effect for the latter relationship (*Cramér's V* = 0.11).

Willingness to forgo car ownership in the future

Along with data on car ownership at the time of the survey and in the two years prior to it, our research was also intended to provide an outlook on future car disposal decisions. Our qualitative interviews that were conducted preceding the surveys revealed that certain car-owning carsharing users wanted to become car-free but preferred to let their car ownership phase out rather than proactively end it. Therefore, we presumed that the impact of the mobility hubs on the car ownership of hub users was still ongoing when we conducted the survey. Consequently, the participants who still owned at least one car by the time of the survey were asked to estimate how likely they were to be car-free in the foreseeable future.

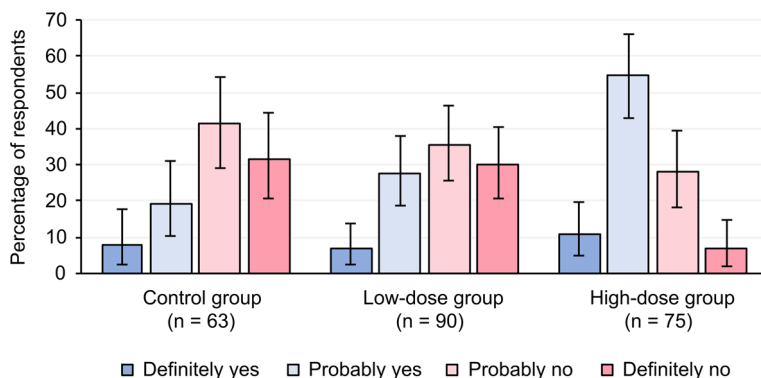


Fig. 6 Willingness of respondents from car-owning households to completely forgo car ownership in the foreseeable future by subsample group. Undecided respondents were excluded. Error bars indicate 95% confidence intervals

Among the car owners surveyed, regular users of mobility hubs were especially interested in car disposal (Fig. 6). More than half of the respondents in the high-dose group indicated that they were likely to end their car ownership in the next few years, and one in ten even had a concrete plan, or conviction, to become car-free. Conversely, in the low-dose group and the control group of car owners, 67% and 73% of the respondents, respectively, reported that they would likely not or definitely not forgo car ownership in the foreseeable future. Hence, the high-dose group again exceeded the other groups. The relationship of the usage frequency of a mobility hub to the willingness to become entirely car-free was statistically highly significant ($\chi^2(6) = 29.89$, $p < 0.001$, *Cramér's V* = 0.26).

Mode usage

Next to impacts on car ownership, we expected the mobility hubs to have an influence on the mode usage of carsharing users. Therefore, we surveyed how often participants typically used certain modes of transportation common in urban areas. The answers are summarized in Fig. 7.

We found that the more frequent use of a mobility hub was associated with significantly greater use of walking ($\chi^2(2) = 8.59$, $p = 0.014$, *Cramér's V* = 0.14) and cycling ($\chi^2(8) = 35.45$, $p < 0.001$, *Cramér's V* = 0.20). Use of public transit also increased with the more frequent use of a mobility hub ($\chi^2(8) = 12.76$, $p = 0.120$), although this relationship was non-significant in a statistical sense. Nonetheless, we detected a small effect between the usage frequencies of mobility hubs and public transit (*Cramér's V* = 0.12). This was further supported by the fact that more respondents in the high-dose group (46%) held a public transit subscription compared to the low-dose and control groups (37% and 39%, respectively). Moreover, greater exposure to a mobility hub was significantly related to less use of private cars as a driver ($\chi^2(8) = 21.42$, $p = 0.006$, *Cramér's V* = 0.16). In contrast, when considering the use of private cars as passengers, we found only minor, non-significant differences ($\chi^2(6) = 3.44$, $p = 0.752$, *Cramér's V* = 0.06).

We also compared the subsamples based on their frequency of carsharing use. Here, it must be mentioned again that our sample only includes those carsharing members who reported making use of such a service at least once a month. Our results basically confirm

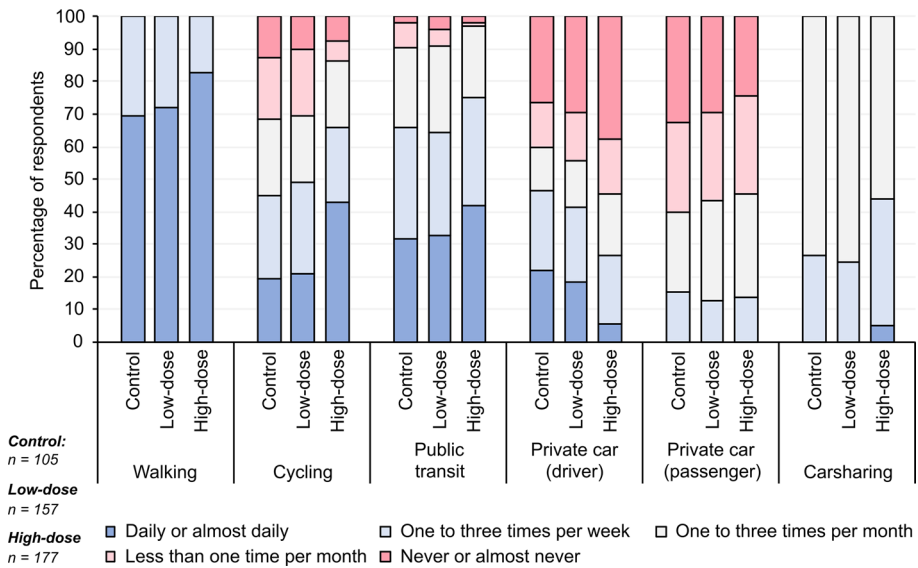


Fig. 7 Transportation mode usage by mode and subsample group

previous findings that even regular carsharing users commonly limit themselves to weekly or monthly carsharing use (e.g., Ko et al. 2019; Namazu and Dowlatabadi 2018). Nevertheless, participants from the high-dose group reported using this option substantially more often. The association between greater use of a mobility hub and more frequent use of carsharing was highly significant ($\chi^2(2)=17.25$, $p < 0.001$, *Cramér's V* = 0.20).

Perceived impact of carsharing on mode usage

Beyond the general usage frequencies of transport modes, we wanted to further examine actual changes in mode usage due to carsharing and whether such changes affected the subsample groups to varying degrees. To do so, we asked respondents to assess whether they relied on certain modes more often or less often as a result of carsharing. Figure 8 shows our findings. It is important to note that this assessment was qualitative and did not allow any quantitative conclusions to be drawn, for example, about the number or lengths of trips that were affected by modal shift. Nonetheless, relevant differences between the groups were again evident, mainly owing to deviations of the high-dose group.

Statistical tests revealed that a higher usage frequency of a mobility hub was associated with a more favorable impact of carsharing on the non-motorized modes of walking ($\chi^2(4)=11.02$, $p=0.026$, *Cramér's V* = 0.11) and cycling ($\chi^2(4)=9.17$, $p=0.057$, *Cramér's V* = 0.10). There was also a highly significant relationship between the use of a decentralized mobility hub and increased public transit usage due to carsharing ($\chi^2(4)=31.58$, $p < 0.001$, *Cramér's V* = 0.19). Moreover, with increasing exposure to a mobility hub, we found considerably higher proportions of respondents who reported less frequent driving of private cars as a result of carsharing ($\chi^2(4)=9.06$, $p=0.060$, *Cramér's V* = 0.10). On the other hand, no significant differences between the groups could be found regarding the influence of carsharing on the use of private cars as a passenger ($\chi^2(4)=6.54$, $p=0.162$,

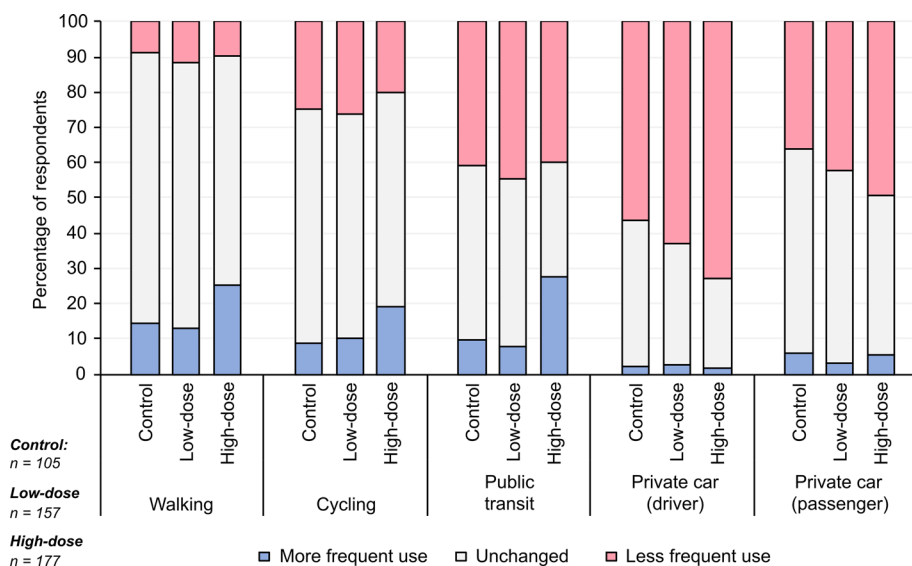


Fig. 8 Perceived changes in transportation mode use due to carsharing usage by mode and subsample group

Cramér's V=0.09), even though the descriptive analysis implied that particularly the respondents in the high-dose group had chosen this mode less frequently because of their carsharing usage.

Substitute modes for disposed of cars

Along with mode usage and how it is influenced by carsharing, we sought to examine whether survey participants who had disposed of a car used different modes of transportation as a substitute, depending on their level of exposure to a mobility hub. For instance, frequent users of mobility hubs might have relied more heavily on carsharing as a substitute mode for disposed of cars. A part of the questionnaire addressed this. If respondents reported that they had reduced or ended their car ownership, they were asked to name the modes of travel that they commonly used for trips that had been previously taken in the disposed of car.

We were not able to conduct a meaningful comparison between the three groups in this regard because the numbers of subjects who had reduced or ended their car ownership were too small in the low-dose group and the control group (19 and 10 cases, respectively). Instead, we compared the high-dose group to the two other groups combined (Fig. 9). Carsharing ($\chi^2(1)=0.34$, $p=0.562$, *Cramér's V*=0.07), public transit ($\chi^2(1)<0.01$, $p=0.999$, *Cramér's V*<0.01), and cycling ($\chi^2(1)=0.20$, $p=0.655$, *Cramér's V*=0.06) were not significantly more or less frequently mentioned as substitute modes for disposed of cars in the high-dose group. Likewise, we found no substantial differences here in the use of other people's private cars ($\chi^2(1)=0.11$, $p=0.735$, *Cramér's V*=0.04) or other cars owned by the respondents ($\chi^2(1)=0.06$, $p=0.813$, *Cramér's V*=0.03). We concluded that even with extensive exposure to a mobility hub, it was not only carsharing that profited from the modal shift resulting from car disposal. Other and even more sustainable modes, such as

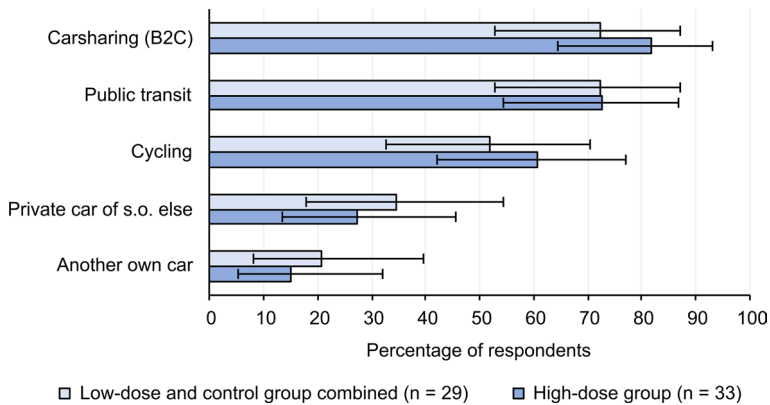


Fig. 9 Transport modes commonly used to replace a disposed of car. Multiple answers were permitted. Error bars indicate 95% confidence intervals. *B2C* business-to-customer

cycling and public transit, also benefited greatly from the amplified reduction in car ownership under the influence of the hubs.

Attitudes toward carsharing

The previous paragraphs have shown that the more extensive use of a mobility hub was accompanied by lower car ownership, less frequent car use, and more extensive use of sustainable modes of transportation. To further explore the causal relationships behind this, we examined the respondents' attitudes toward carsharing. Here, we expected that regular use of a decentralized mobility hub would be associated with a more positive perception of carsharing. As with the aforementioned assessment of attitudes toward certain modes of transportation, we also measured the specific perception of carsharing using a five-point Likert scale. The set in this case comprised nine items, which we did not reduce to factors, since we were interested in the level of agreement with each individual statement. Figure 10 shows the average ratings of the nine statements by subsample group.

All three groups perceived the costs of carsharing (Item CS_1 : $F(2, 436)=0.21$, $p=0.810$, $\eta^2<0.01$) and the effort for booking a carsharing vehicle (Item CS_2 : $F(2, 436)=0.86$, $p=0.424$, $\eta^2<0.01$) very similarly. This is plausible since the prices, as well as the booking and payment processes, are not influenced by the mobility hub but are instead set by the carsharing operators. On the other hand, for items where we expected a clear influence by the hubs, significant differences in the ratings were indeed evident. Carsharing users with frequent use of a mobility hub assessed both the typical distances to the next available carsharing vehicle (Item CS_3 : $F(2, 436)=14.04$, $p<0.001$, $\eta^2=0.06$) and the usual amount of time needed to find a parking space for a carsharing vehicle in their neighborhood (Item CS_4 : $F(2, 436)=3.40$, $p=0.034$, $\eta^2=0.02$) significantly more positively. They also attached substantially higher importance to dedicated carsharing parking spaces (Item CS_5 : $F(2, 436)=30.97$, $p<0.001$, $\eta^2=0.12$). At the same time, the regular use of a decentralized mobility hub was associated with a stronger general appreciation of carsharing. Respondents in the high-dose group more frequently stated that carsharing enabled or supported them to reach

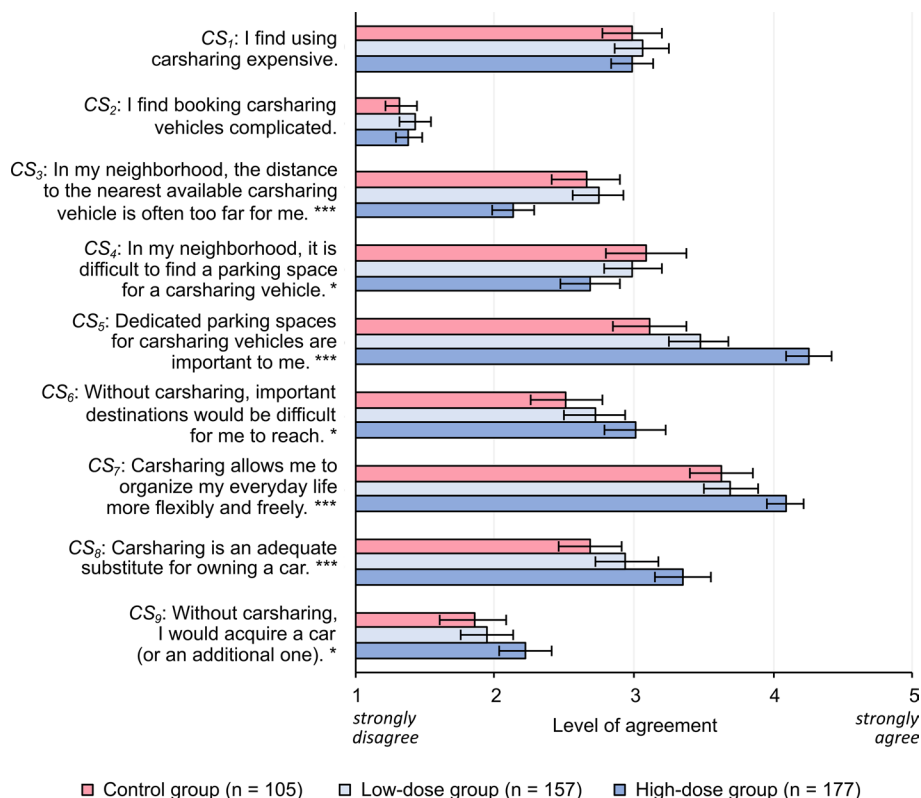


Fig. 10 Attitudes toward carsharing. The figure depicts the mean level of agreement with each statement by subsample group. Error bars indicate 95% confidence intervals. Significance between groups is indicated by the following: * $p < 0.05$; *** $p < 0.001$

important destinations (Item CS₆: $F(2, 436) = 4.22$, $p = 0.015$, $\eta^2 = 0.02$) and that they could organize their everyday life more freely and flexibly with the help of carsharing (Item CS₇: $F(2, 436) = 8.14$, $p < 0.001$, $\eta^2 = 0.04$).

In this respect, it is not surprising that the individuals in the high-dose group rated the suitability of carsharing as an adequate substitute for their own car as significantly higher (Item CS₈: $F(2, 436) = 9.00$, $p < 0.001$, $\eta^2 = 0.04$). Fittingly, regular users of mobility hubs would be more inclined to purchase a private car in the hypothetical case of carsharing services being discontinued (Item CS₉: $F(2, 436) = 3.51$, $p = 0.031$, $\eta^2 = 0.02$). However, the responses to the latter item also showed that the majority of carsharing users in all the subsample groups would not consider purchasing a car as a desirable option even without carsharing.

For those seven items for which we found significant differences, we post-hoc compared the groups pairwise. This comparison revealed that for six of the seven items, there were only significant differences between the high-dose group and the other two groups but not between the low-dose group and the control group. Only for agreement with the statement, “Dedicated parking spaces for carsharing vehicles are important to me,” did the low-dose group differ significantly from the control group ($t(225.25) = -2.05$, $p_{adj} = 0.041$, $r = 0.14$).

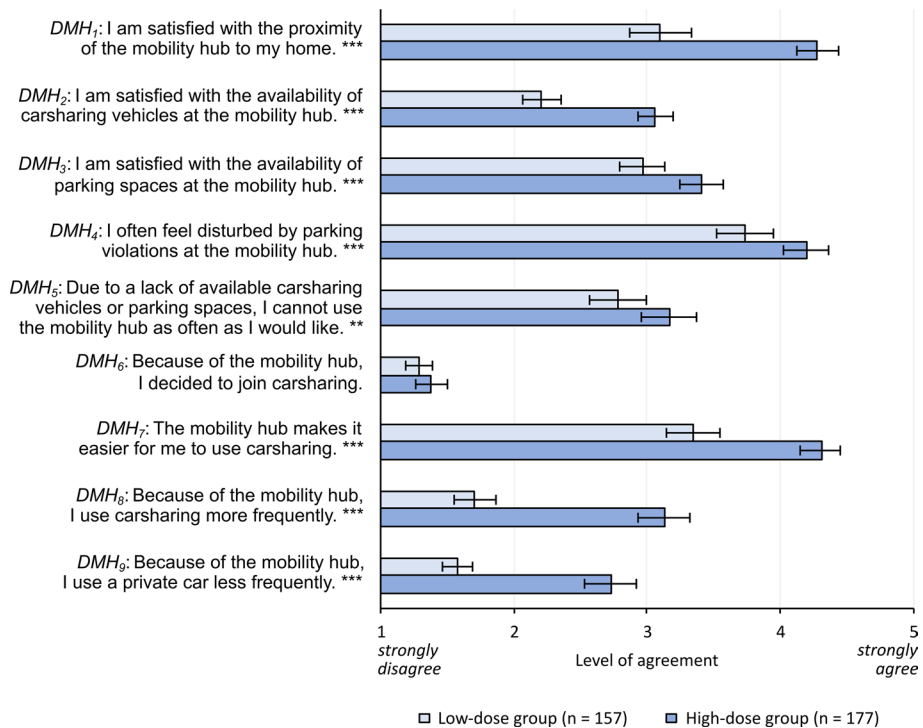


Fig. 11 Attitudes toward decentralized mobility hubs. The figure depicts the mean level of agreement with each statement by subsample group. Error bars indicate 95% confidence intervals. Significance between groups is indicated by the following: ** $p < 0.01$; *** $p < 0.001$

Attitudes toward decentralized mobility hubs

Participants who had already gained experience with the new mobility hubs at the time of the survey were given an additional set of nine statements on a five-point Likert scale. The statements covered attitudes toward the hubs and the perceived impact of these new offers on the use of carsharing and private cars. In this way, we sought to understand not only how different usage frequencies of the mobility hubs affected their perception and impact but also why respondents in the low-dose group had not used the hubs more often. As with the items on attitudes toward carsharing, we analyzed these items individually rather than by forming factors from them. The levels of agreement in the high-dose group and the low-dose group are presented in Fig. 11. Because of their lack of experience with mobility hubs, the control group was excluded here.

There was a highly significant difference in satisfaction regarding the proximity of mobility hubs to respondents' homes (Item DMH₁: $t(285.87) = 8.30$, $p < 0.001$, $r = 0.44$). A more in-depth investigation confirmed an expected relationship between the distance to the hub and its perception and actual utilization. Satisfaction regarding proximity was very pronounced up to a limit of 200 m; satisfaction fell sharply above this threshold. At the same time, 63% of the respondents from the high-dose group, but only 31% from the low-dose group, lived within a distance of 200 m or less from the mobility hub.

Besides distance, respondents with infrequent use of the new hubs were also significantly less satisfied with the availability of carsharing vehicles (Item DMH₂: $t(326.01)=8.57$, $p<0.001$, $r=0.43$) and vacant carsharing parking spaces (Item DMH₃: $t(328.08)=3.72$, $p<0.001$, $r=0.20$) at the mobility hubs. This suggests that the rarer use of hubs among the low-dose group was not solely based on voluntary choices but also resulted from the heavier influence of these usage barriers. However, both groups indicated that they were frequently disturbed by parking violations at mobility hubs. This perception was significantly stronger in the high-dose group (Item DMH₄: $t(303.17)=3.36$, $p<0.001$, $r=0.19$). We assumed that greater usage of the mobility hubs was accompanied by encountering parking violations more often, thus leading to this difference. Furthermore, it was evident in both groups that the hubs could not be used as often as desired due to occasional lack of vacant vehicles or parking spaces. Again, this perception was substantially more prevalent in the high-dose group (Item DMH₅: $t(330.40)=2.59$, $p=0.010$, $r=0.14$), despite their already comparatively frequent use of the hubs.

Regarding the statement “Because of the mobility hub, I decided to join carsharing,” we found no statistically significant differences (Item DMH₆: $t(329.96)=1.15$, $p=0.252$, $r=0.06$), but we did find exceptionally low levels of agreement in both intervention groups. We can presume that the active carsharing users in our sample were already carsharing members before the implementation of decentralized mobility hubs.

Responses of the two intervention groups to the statement, “The mobility hub makes it easier for me to use carsharing,” demonstrated that regular users of the mobility hub significantly more strongly perceived the new amenities to be supportive of carsharing use (Item DMH₇: $t(292.57)=7.41$, $p<0.001$, $r=0.40$). Nevertheless, even the respondents who only used the hub rarely indicated a certain appreciation for the amenities through their ratings of this statement. However, the low-dose group did not reveal any noteworthy actual impact of mobility hubs on the usage frequencies of carsharing and private cars. The high-dose group, in contrast, agreed significantly more strongly that their carsharing usage increased (Item DMH₈: $t(325.41)=11.61$, $p<0.001$, $r=0.53$), while their use of private cars decreased (Item DMH₉: $t(278.56)=10.32$, $p<0.001$, $r=0.53$), due to the mobility hubs.

Perceived impact of decentralized mobility hubs on decisions against car ownership

In addition to their influence on carsharing and private car use, we delved deeper into the role that mobility hubs played in the decisions against car ownership. Hub users who had disposed of their own car or had suspended car purchases were asked how much the hubs had influenced their decision. Figure 12 depicts the responses of the high-dose group, which were of particular interest to us. Accordingly, of the respondents considered herein, only 30% stated that there was no relationship between the mobility hub and their decision to dispose of a car. In contrast, 55% of individuals in the high-dose group rated the size of the hub’s impact on the disposal of their own car as very large to at least medium. In the deliberate decision not to acquire a car, the mobility hubs exerted at least a medium-sized impact even in 59% of the cases, and only one in five respondents in the high-dose group attributed no influence to the new hubs regarding their decision.

As expected, the subjects in the low-dose group perceived the impact of the mobility hubs as being much smaller. Of the 19 individuals who had disposed of a car in this group, 37% estimated a weak influence, and the remaining 63% reported no impact at all. Of the

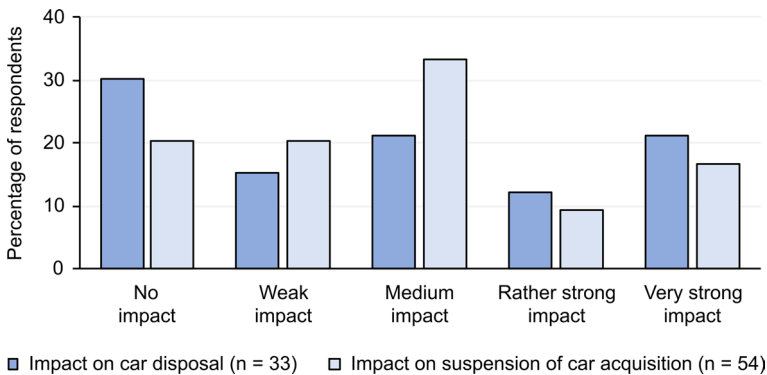


Fig. 12 Perceived impact of decentralized mobility hubs in the decision to dispose of a car or to suspend car acquisition. The figure shows only responses from regular users of decentralized mobility hubs (i.e., respondents in the high-dose group) who had effectively committed to one of these decisions

33 people in the low-dose group who had suspended car acquisition, 33% estimated the impact as weak, and 67% estimated it as nonexistent.

Discussion

Summary of results

In this study, we compared carsharing users with frequent or rare use of mobility hubs to each other, as well as to carsharing users who were not exposed to such facilities. We found that the regular use of a decentralized mobility hub was associated with significantly lower car ownership and a shift in mode usage in favor of sustainable transport modes. Differences in sociodemographics, basic attitudes toward transport modes, or carsharing types used could be ruled out as a primary cause of these findings, as the groups compared were very similar in these aspects. Instead, our results indicated a causal influence of mobility hubs. Their effects can be attributed to the increased attractiveness and usability of carsharing due to more conveniently accessible vehicles and dedicated parking spots in neighborhoods that are otherwise characterized by a scarcity of parking spaces. These characteristics in turn lead to the findings that the frequent users of mobility hubs were more likely to assess carsharing as an adequate substitute for private cars and were, therefore, willing to actually reduce their car ownership or to refrain from acquiring a car. Our contribution thus validates previous papers that have emphasized the high importance of easily accessible carsharing vehicles and exclusive parking spaces to strengthen carsharing as an alternative to owning and using private cars (e.g., Chen et al. 2018; De Lorimier and El-Geneidy 2013; Dowling and Kent 2015; Liao et al. 2020). It is probable that the effects of existing mobility hubs on car ownership will increase even further, as a sizeable share of hub users expressed an intention to dispose of their cars in the coming years.

However, the enhanced attractiveness of carsharing through mobility hubs benefits not only carsharing itself but also other more environmentally friendly modes. The reason for this seems to be an indirect effect of the increased reduction of car ownership under the influence of mobility hubs. Even with frequent use of the hubs, carsharing users reported

replacing disposed of cars not only with carsharing but also to a large extent with public transit and cycling. From previous research (e.g., Kent 2014; Martin and Shaheen 2011b), it was already known that carsharing, via its effect on car ownership, can result in an overall reduction of car use and a more extensive usage of sustainable means of transportation. In our study, we were able to demonstrate that mobility hubs magnify these effects.

Nonetheless, it must also be noted that the impact of mobility hubs can be severely hampered by usage barriers, such as access distances that are deemed too long. Positive perception, actual use, and ultimately the effectiveness of the hubs was found to be greatest up to a distance of 200 m and then decrease steeply beyond that point. This outcome is in line with previous research findings that most carsharing users only accept short distances to or from vehicles and parking spaces (e.g., Ampudia-Renuncio et al. 2018; Costain et al. 2012; Herrmann et al. 2014; Rotaris et al. 2019). In addition, the insufficient availability of vacant carsharing vehicles and parking spots at the hubs proved to be a problem. This was further exacerbated by parking violations, as private cars recurrently occupied parking spaces intended for carsharing vehicles only. We found that infrequent users of mobility hubs more strongly perceived usage barriers. The data suggest that these respondents would use the hubs more frequently if there were a better availability of vehicles and parking spaces and if the hubs were located closer to the respondents' homes. Limitations in the usability and actual use of the mobility hubs thus meant that the hubs were not able to deliver their full potential, which was also evident in the inter-group comparisons; regarding car ownership, mode usage, and attitudes toward carsharing, we did not find meaningful differences between carsharing users with infrequent hub use and carsharing users from the control sites without any access to a mobility hub. On the other hand, our study shows that decentralized mobility hubs provide substantial support for carsharing when their amenities can be used regularly.

Limitations of this study

When interpreting our results, some limitations of our research need to be considered. The main weakness is the absence of pre-intervention data. Due to organizational constraints, we were not able to conduct a survey prior to the implementation of the mobility hubs. Therefore, we had to resort to a post-test only quasi-experimental design. We partially compensated for this by using retrospective survey questions and by integrating a suitable control group into our research. Nevertheless, the internal validity of this study does not reach the validity of quasi-experiments, including both pre-intervention and post-intervention measures (Leatherdale 2019). Furthermore, questions that refer to the past are prone to biases regarding the recall and attribution of certain decisions (Becker et al. 2018), although we do not expect that such biases fundamentally altered the results of our research.

Another limitation was the small size of the subsample groups, which affected the statistical power of our analyses. First, the sample size was a result of the spatial limitation of our study sites to a few residential neighborhoods. Second, even in inner-city areas with a large number of available carsharing services, the majority of the population did not hold a carsharing membership. Moreover, many carsharing members used carsharing only rarely, which further reduced the number of residents relevant to this study. However, despite the relatively low study power, the consistent results build confidence in our findings. Where statistical significance was missed, descriptive analysis generally indicated that between-group differences trended in the expected direction.

Implications for policy, practice, and future research

The results of the evaluation of decentralized mobility hubs have aided in the decision to vastly expand the number of hubs in Hamburg in the current decade. The emphasis here will be on a supply-oriented increase in the number of hubs in high-density urban areas. This increase is aimed at achieving closer spatial coverage, especially in the inner city of Hamburg, and spreading the impact of the hubs to larger parts of the city's population.

We hope, however, that the implications of our research will not be limited to Hamburg. Many major European cities exhibit similar urban structures and experience problems resulting from high car ownership rates and extensive car use. Meanwhile, the proliferation of carsharing services is reaching a growing number of cities. We therefore expect that mobility hubs will gain momentum and that many cities will consider the implementation of hubs of different sizes and compositions in the coming years.

Nevertheless, based on the experiences in Hamburg, we also assume that the establishment of mobility hubs will at times encounter skepticism and criticism. Policy-makers, planners, or the population at large may question whether the allocation of designated space for carsharing through mobility hubs actually leads to support for this mobility option and whether such support is in the interest of sustainable mobility after all. In this regard, we believe that our research can contribute, albeit far from exhaustively, to closing the evidence gap. Furthermore, opinions are likely to diverge on the topic of where the space for mobility hubs should be found. Currently, a very uneven allotment of street space for the advantage of private cars represents the normality of the inner-city residential areas of most European cities. Our research shows that withdrawing space for mobility hubs from public on-street parking in particular, as is the practice in Hamburg, is a reasonable measure of street space reallocation that actually helps reduce private car ownership and use.

Ideally, an increasing dissemination of mobility hubs should be paralleled by further, more comprehensive studies that rely on larger samples or additional methodological approaches (e.g., before-after-comparisons, travel diaries). Our paper is focused on small hubs in high-density urban areas. Future research might examine other types of mobility hubs as well, such as larger central hubs, locations outside inner-city districts, or hubs that offer other mobility services than carsharing. The ultimate goal should be to provide a solid empirical basis for assessing which type of mobility hub is best suited to support sustainable mobility in each circumstance.

Conclusion

This study confirms that the implementation of decentralized mobility hubs in high-density inner-city residential neighborhoods amplifies the positive effects of carsharing on sustainable mobility. By transforming public on-street parking space into conveniently accessible parking spots for both free-floating and station-based services, carsharing is enhanced as a mobility alternative to owning a car, thereby allowing carsharing to make a significantly greater contribution to the overall reduction of car use and car ownership. In the future adoption of this approach, however, care must be taken to ensure that urban residents have as unfettered access to mobility hubs as possible. For this purpose, the close spatial coverage of residential areas is essential. It will also be of crucial importance to obviate usage

barriers at mobility hubs (e.g., barriers caused by unauthorized parking or a lack of vacant carsharing vehicles).

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Availability of data and materials The datasets generated and analyzed during the current study are not publicly available due the fact that they constitute an excerpt of doctoral research in progress but are available from the corresponding author on reasonable request.

Declarations

Conflict of interest On behalf of both authors, the corresponding author states that there is no conflict of interest.

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