# Vaccination Dashboard Development during COVID-19: A Design Science Research Approach

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**Abstract.** The COVID-19 pandemic has affected the lives of people worldwide since the beginning of 2020. Since vaccines against COVID-19 have become available, the issue of vaccination has become increasingly important. Accordingly, vaccination dashboards are provided to inform the public about COVID-19 vaccination developments. In our study, we used a design science research (DSR) approach to explore what information vaccination dashboards should provide and how they should be designed. In addition to an initial literature review, we analyzed existing vaccination dashboards and derived information categories. Thereafter, we conducted an online survey to identify the most important metrics from a user's perspective. Our results indicate that, in addition to vaccination coverage, a comparison of vaccination efficacy and side effects is important. Subsequently, a click prototype was developed and expert interviews were carried out to determine how vaccination dashboards should be designed and which technical issues should be considered.

**Keywords:** Vaccination dashboards, pandemic dashboard development, vaccination metrics, user interface, design science research

## 1 Introduction

Since the start of 2020, the COVID-19 pandemic with its consequences has influenced people all over the world. Initially, for a period of time, the focus was primarily on the infection development. COVID-19 dashboards have been in frequent use to present the relevant information regarding the infection situation to the population in a compact manner. In particular, the Johns Hopkins University (JHU) COVID-19 dashboard [1] gained global popularity [2]. With regard to dashboards that convey information on infectious diseases including COVID-19, there is literature available that deals with the design, content and functionalities of these dashboards [3-6].

Since vaccines against COVID-19 have become available, information provision regarding vaccinations has become increasingly important. An increased need for information and skepticism about the COVID-19 vaccination might be caused by the rapid approval of the novel vaccines [7] and negative examples of fast vaccine development in the past such as the development of the vaccine Pandemrix against swine flu (H1N1) [8]. Therefore, it is not surprising that vaccination dashboards were

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developed to provide the public with relevant information related to COVID-19 vaccination. The providers of these vaccination dashboards range from government institutions [9] to public online newspapers [10] and research institutions [11]. When visiting the dashboards, the user will notice that certain information is consistently available, while other information sets differ from one dashboard to the next. There are also differences with regard to the design and the level of interactivity. The principles of successful COVID-19 vaccination dashboard development have not yet been scientifically examined, but would be important for vaccination dashboard providers to address the target group well. In order to fill this research gap, we developed design principles (DPs), based on an analysis of existing vaccination dashboards using the design science research (DSR) approach by Peffers et al. [12] to create a prototype that represents a user-centered instantiation of our DPs. We focused on user preferences and analyzed the relevant information and design of the user interface (UI), with the aim of answering the following research questions (RQs):

*RQ1: Which information and metrics regarding COVID-19 vaccination are relevant for vaccination dashboard users?*

*RQ2: How should the determined important metrics be displayed on a user-centered vaccination dashboard with regard to the design and which technical issues need to be considered?*

As vaccination dashboards are publicly available, all people are considered as potential users. The intended use can range from simple information purposes to informed decision making regarding an own vaccination. In addition to identifying the metrics relevant to users, it is important to investigate how this information can be presented in a user-friendly way. To answer the RQs, we structured this article as follows. In Section 2, we explain the theoretical background of dashboards in general and provide insights into publications dealing with COVID-19 dashboards. In Section 3, we describe our research methodology and the DSR approach, which is concretized in Section 4 by deriving issues (Is) and elaborating meta requirements (MRs) as well as DPs. Subsequently, in Section 5, we describe our analysis results in detail. In Section 6, we discuss our findings and conclude our contribution with limitations of our study as well as an outlook for future research.

## 2 Background and Related Work

In general, dashboards present the most relevant information visually on one screen. The interactivity of dashboards enables the user to find further information on relevant aspects to be able to draw conclusions [13]. A meaningful dashboard design can prevent information overload and support the user in decision making. Information is imported from various sources and presented to the user in a compressed form [14]. Dashboards have been used in a variety of humanitarian crises in the past. They served as a tool for decision-makers in wars and terrorist attacks [15, 16] but also in natural disasters such as storm floods [17] or forest fires [18]. Dashboards have also been used in epidemics such as dengue fever [19], the annual flu season [5, 20] and malaria [21].

Particularly for the monitoring and visual representation of infection events during the COVID-19 pandemic, dashboards have regained considerable prominence at the local, national and global levels. From a scientific point of view, the representation of information via dashboards in the COVID-19 pandemic has already been studied from different foci. Especially at the outset, there were several studies that dealt with the conceptualization of dashboards for hospitals to provide an effective overview of and a forecast for intensive care bed utilization [22–24]. There are also publications dealing with the conceptualization of COVID-19 dashboards for the general public. Some authors describe the DPs that should be used to implement dashboards for infection events at a national or global level and, in some cases, developed prototypes. For example, one publication outlines the DPs of the most famous dashboard of the COVID-19 crisis, that of the JHU [6], and another one provides insights on how to improve the geospatial German national dashboard [25]. Several authors, among others Berry et al. [26], Ashofteh and Bravo [27] and Beltran et al. [28], dealt with technical aspects such as data quality and security, and less with content aspects such as metrics. Devasia et al. [2] compared dashboards, focusing on tracking capabilities. Pöhler et al. [29], Ivanković et al. [30] and Fareed et al. [31] compared dashboards from different states or countries in terms of visualization, functionality and content. However, they only refer to infection data and not to vaccination data.

Even before the outbreak of the COVID-19 pandemic, Bollaerts et al. [32] addressed how a general vaccination dashboard could be designed, without reference to a specific disease. However, the feedback from their design was based on only a small number of end users and does not incorporate COVID-19-specific characteristics such as the potential need for a second dose of vaccine. Since the outbreak of the COVID-19 pandemic and the almost simultaneous development of vaccines, a number of publications have also addressed the ways in which the public can be informed about vaccination and encouraged to get vaccinated. For example, French et al. [33] investigated how a vaccination campaign against COVID-19 can be conducted and the possibilities of transparent marketing. However, the possibility of neutral reporting via dashboards is not discussed. Berry et al. [34] elaborate on ways to collect data to provide valid aggregate information on the progress of vaccination at the national level. Wouters et al. [35] developed a dashboard to highlight key characteristics of 26 leading vaccine candidates to construct a basis for the comparison of different vaccines. However, to the best of our knowledge, there has not yet been a publication that addresses which data in which form will be highly relevant to the population on a publicly available COVID-19 vaccination dashboard. Thus, by adopting the DSR approach, we generate DPs for user-centered vaccination dashboards and create as well as evaluate a prototype.

## 3 Research Approach

To answer the RQs, we chose the DSR approach according to Peffers et al. [12]. By applying three cycles, we generated a vaccination dashboard prototype that contains all relevant information for the user at a glance. The applied procedure is illustrated in

Figure 1. For the evaluation strategy, we refer to Sonnenberg and vom Brocke [36], who specified the criteria for the review of the DPs for each cycle. Following Peffers et al. [12], our artifact development was based on problem identification. To find a solid basis, we conducted a systematic literature search following vom Brocke et al. [37], to identify challenges, problems and Is in creating practical dashboards for later prototyping (Section 4). Referring to Cooper [38], we aimed at the integration of the findings based on the research outcomes of conceptual elaborations. Furthermore, we adopted a neutral perspective when analyzing this representative sample addressed to the general population.

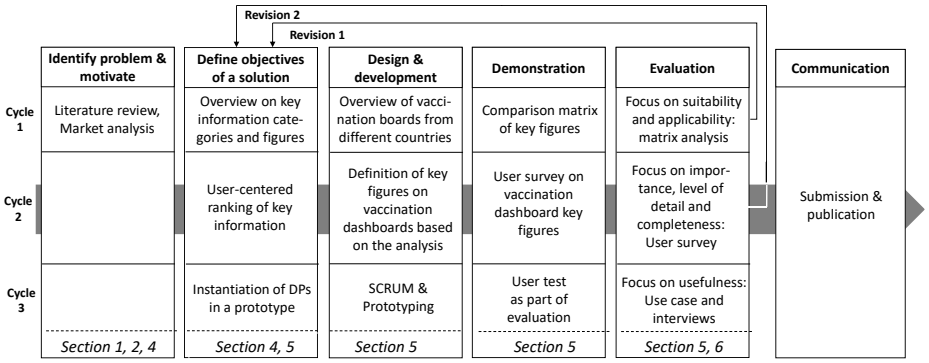


**Figure 1.** DSR approach according to Peffers et al. [12]

We searched for relevant literature in the databases of Scopus, EbscoHost and PubMed using the search string (dashboard* AND (develop* OR representat* OR data) AND (issue* OR challenge*)) and performed forward and backward searches. We prioritized dashboards that deal with humanitarian crisis situations, including infectious diseases, in order to achieve a focus on the content of our planned prototype solution. After filtering by title, abstract and full text, the literature search yielded 13 relevant papers related to current problems and challenges in dashboard creation.

Based on the literature review, we extracted Is from the relevant papers. We then held a workshop and derived MRs for the vaccination dashboard from the Is. Based on the MRs, we developed DPs guided by Gregor et al.'s anatomy [39] (Section 4). The workshop participants were four designated domain experts from the fields of dashboard development or from the health sector, as Sutton and Arnold [40] request. We followed Venable et al.'s FEDS framework [41] in terms of evaluating DPs and prototype development (Section 5). In doing so, we focused on the content of vaccination dashboards through analyzing existing vaccination dashboards (evaluation cycle 1) and conducting a user survey (evaluation cycle 2) before instantiating the prototype and evaluating its functional, content and technical aspects by conducting semi-structured interviews with experts, according to Gläser and Laudel [42] and analyzing them with a qualitative content analysis, according to Mayring [43], using QDA Miner (evaluation cycle 3).

## 4 Issues, Meta-Requirements and Design Principles

Based on the relevant literature, we identified nine Is. In a workshop, the experts brainstormed solutions to address these hurdles and derived eight MRs, which we were able to bundle into three DPs. Figure 2 illustrates the Is identified from the literature and their relationship to the MRs and DPs that can be applied to vaccination dashboards.

First, it is a problem if a dashboard is not accessible for everyone and, accordingly, does not provide equal benefit for all potential users (I1) [5]. MR1 constitutes that a dashboard should be barrier-free. Regarding the UI of the main screen, the literature revealed the challenge to provide enough interactivity (I2) [4, 13]. It would be problematic if contextual information was not available on the dashboard (I3) [5]. To solve this, MR2 aims at interaction with the dashboard and user-specific customization options. Context-specific information on a dashboard can refer to demographic information such as income, age and geographical regions. With MR1 and MR2, we can conclude **DP1**: *Enable barrier-free context-specific information reception by providing a UI allowing interaction with filter and selection options because this enables users to find the needed information for their personal situation*.

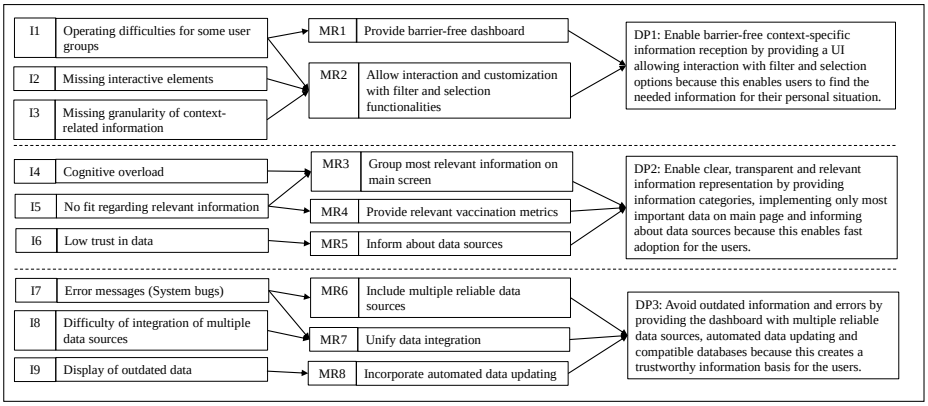


**Figure 2.** Issues, meta-requirements and design principles

Regarding the information amount to be displayed, too much information at once is counterproductive and can lead to information overload (I4) [44]. Research about the human limits of processing information proves this, by concluding that a person can capture five to nine units of information in short-term memory at the same time [45]. In addition, it can be a problem that the information contained on a dashboard does not match the information relevant to the users (I5) [25, 46, 47]. MR3 remedies these Is by specifying that relevant information should be categorized on the main screen. Moreover, I5 leads to MR4, to provide relevant vaccination metrics on the dashboard. Furthermore, it can lower the user's acceptance if the data is provided without trustworthy data sources (I6) [48]. Accordingly, data sources should be included on vaccination dashboards (MR5). With I4 to I6 and MR3 to MR5, **DP2** can be generated: *Enable clear, transparent and relevant information representation by providing*

*information categories, implementing only most important data on main page and informing about data sources because this enables fast adoption for the users.*

Regarding data integration in the backend, system errors are a problem (I7), whereby they can be caused by erroneous data or blank data [5]. Ultimately, several reliable data sources should be used (MR6). However, integrating multiple data sources can be challenging (I8) [49], so the data itself and the data integration process should be standardized (MR7). With regard to the aim to provide real-time data, displaying outdated information is assessed as problematic for dashboards (I9) [3, 29, 32]. This leads to MR8, to continuously import current and automatically updated data. MRs 6 to 8 lead to **DP3**: *Avoid outdated information and errors by providing the dashboard with multiple reliable data sources, automated data updating and compatible databases because this creates a trustworthy information basis for the users.*

To implement DP1 and DP3, a lot of design knowledge is available from previous publications that deal with creating dashboards [4, 5, 25]. However, design knowledge to implement DP2 has not yet been scientifically developed, since it involves specific content with explicit reference to COVID-19 vaccinations. Therefore, in the first two evaluation cycles, we mainly focus on enabling the presentation of relevant content required for DP2 by identifying, categorizing and prioritizing content. For the third cycle, DP1 and DP3 will be involved more strongly through the prototype instantiation.

# 5 Results and Evaluation

## 5.1 Evaluation Cycle 1: Existing Dashboards

Analyzing existing vaccination dashboards allowed us to determine the status quo and to compile the information provided by the dashboards. The dashboards were analyzed in terms of their metrics and functionalities, referring to DP1 and DP2. The information in this practical analysis was determined inductively. The analysis results are displayed in Table 1. Regarding the categories, "x" indicates that the metric was included. Regarding the functions, "+" means an extensive, "o" partial, and "-" non-existent implementation of the element. We selected eleven frequently used, mainly governmental, vaccination dashboards, but also included those from research institutions and well-known newspaper publishers. We analyzed the governmental vaccination dashboards of Germany [9], Switzerland [50], Austria [51], the USA [52], the United Kingdom [53], the Netherlands [54] and India [55]. These were supplemented by dashboards from the education sector, namely the JHU [11], Oxford University (OWID) [56], and from a German (online) newspaper, Die Zeit [10]. Lastly, the Environmental Systems Research Institute (ESRI) dashboard [57] that displays the information on one screen without the need to scroll down, was included. With the analysis results, conclusions could be drawn to answer RQ1.

The comparison shows that some metrics are used across all dashboards, particularly those that represent the total vaccination numbers for a country’s population, both in absolute and relative terms. In addition, the daily doses administered are listed consistently. Information on population parts also plays a major role. Regarding this,

information on vaccination progress by age groups and in regions is particularly important. We were also able to group the information provided on the dashboards into metrics regarding (1) *total population*, (2) *population parts*, (3) *forecasts and calculations*, (4) *country comparisons*, (5) *additional information*, (6) *side effects*, (7) *deliveries, stock and orders* and (8) *own vaccination*. The information can be further differentiated according to the respective vaccines. Timelines are often used to illustrate the metrics adequately.

**Table 1.** Metrics and interaction elements on analyzed COVID-19 vaccination dashboards

| Category | Vaccination metric | JHU | OWID | GER | AUT | SUI | IND | USA | NL | UK | Zeit | ESRI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Total population | Total vaccination rate | x | x | x | x | x | | x | x | x | x | x |
| | Vaccination rate first vaccination | x | x | x | x | x | | x | x | x | x | x |
| | Total doses administered | x | x | x | x | x | x | x | x | x | x | x |
| Population parts | Vaccinated doses per manufacturer | | x | x | | x | | x | x | | x | x |
| | Vaccination progress by age | | x | | x | x | | x | x | x | x | |
| | … by regions within a country | x | | x | x | x | x | x | | x | x | x |
| | … by gender | | | | x | | | x | | | | |
| | Vaccinated share per manufacturer | | | x | x | x | | | | | x | |
| Forecasts/ Calculations | Time to herd immunity | | | x | | | | | | | x | |
| | Effects (deaths avoided etc.) | | | | | | | | x | | x | |
| Country comparison | Country comparison of progress | x | x | | | | | x | | | x | |
| | Approved vaccines per country | | x | | | | | | | | | |
| Additional information | Daily doses administered | x | x | x | x | x | x | x | x | x | x | x |
| | Vaccination milestones | | | x | | | | | x | | | |
| | Percentage willing to be vaccinated | | x | | | | | | x | | | |
| Side effects | Side effects | | | | | x | | | | | | |
| Deliveries, stock and orders | Deliveries by manufacturer | | | x | x | | | x | x | | x | |
| | Vaccine orders | | | | x | | | | x | | | |
| | Stock by manufacturer | | | | | | | | x | | | |
| Own vaccination | Vaccination locations | | | | | x | | | | | | |
| | Link for vaccination registration | | | | x | | x | | | | | |
| **Category** | **Function** | **JHU** | **OWID** | **GER** | **AUT** | **SUI** | **IND** | **USA** | **NL** | **UK** | **Zeit** | **ESRI** |
| Interaction | Cursor position | + | + | + | + | + | - | + | + | + | + | o |
| | Click option | o | + | o | + | + | + | + | + | + | o | + |
| | Filtering (drill down etc.) | - | o | o | o | + | - | o | o | o | o | o |
| | Design customization | - | + | - | + | - | - | - | - | - | - | - |
| | Commenting functions | - | - | - | - | - | - | - | - | - | + | - |
| | Downloading function | - | + | + | - | + | - | + | + | + | - | - |
| Access | Barrier-free elements | - | - | + | o | o | o | - | o | o | - | - |
| Data information | Data sources displayed | + | + | + | + | + | + | + | + | + | + | + |
| | Last data update displayed | + | + | + | + | + | + | + | + | + | + | + |

JHU: Johns Hopkins University; OWID: Our World in Data; GER: Germany; AUT: Austria, SUI: Switzerland; IND: India; NL: Netherlands; UK: United Kingdom; ESRI: Environmental Systems Research Institute

Almost all dashboards offer basic interactive elements, but in varying degrees. Mostly, further information is displayed by placing the cursor on an element and integrating click options. Several dashboards also provide filter options, such as drill-

down menus, to obtain information on population subgroups or selected countries in an international comparison. However, only a few offer the possibility to customize the presentation form of information, for example, in the form of tables or bar charts. Only the Zeit implements a commenting function, whereas more dashboards offer the download of related data sets. With regard to the accessibility, the German government's dashboard provides many options, such as language selection, as well as explanations in easy language and sign language, and a media library. Others do not consider accessibility to this extent. However, the dashboards consistently provide information about the data sources and the time of the last update, although this is not always up-to-date on a daily basis.

### 5.2 Evaluation Cycle 2: Questionnaire

Based on the dashboard analysis results, we created a quantitative online survey. Respondents indicated the relevance of the respective metrics from their point of view on a symmetric 7-point Likert scale that included response options from "1 = strongly disagree" to "7 = strongly agree". The item generation was largely deductive, as the metrics were mostly derived from the dashboard analysis. Items with regard to the *effectiveness* (9) were included as an additional category after a brainstorming process among the authors. Ultimately, 35 metrics were included. By integrating a free text field, it was possible to gain new metrics relevant to the participants. A quantitative analysis of the survey results was carried out, including descriptive statistics. We wanted to determine which metrics are particularly important to users and which are dispensable. The MTurk platform was used for recruiting participants. We followed data quality assurance guidelines from Hunt and Scheetz [58] to ensure that we accessed qualified MTurk participants. In July 2021, 141 participants completed the survey. Because of the survey language, German language skills were required. After quality controls that included a minimum processing time as well as control questions, 107 online surveys were considered for the analysis. 43% of the participants were female and 57% male. 74% were younger than 50 years, with the dominant age group between 18 and 29 years. Noticeable survey results are illustrated in Table 2.

The highest relevance is attributed to the national vaccination coverage, which also had the lowest standard deviation. Accordingly, *total population vaccination* plays uniformly a central role for the users (M = 6.15, SD = 0.96). In addition, the indication of the *effectiveness* of the vaccination is particularly relevant, both regarding the vaccines available (M=5.91) and regarding the COVID-19 mutations (M = 5.89). The possible side effects of the respective vaccines should also be included (M = 5.67). It is striking that both the side effects and the protection against a COVID-19 infection have a particularly high relevance to the participants. Accordingly, it can be stated that displaying these two information sets contributes to an objective and balanced information provision on vaccination dashboards. In contrast, we also identified less important information which can be dispensable on a condensed main screen. This includes information on specific *population parts* as well as *supplies, stock and orders*. Vaccination progress by gender (M = 3.33) and by level of education (M = 3.44) received the lowest values.

**Table 2.** Extract of results of the online survey, n=107

| Rank | Information (Category number in brackets) | Mean | SD |
|---|---|---|---|
| 1 | Total vaccination rate (1) | 6.15 | 0.96 |
| 2 | Overall effectiveness of specific vaccine (9) | 5.91 | 1.23 |
| 3 | Effectiveness of vaccine against mutations (9) | 5.89 | 1.20 |
| 4 | Time horizon for maximal protection after last dose (8) | 5.70 | 1.35 |
| 5 | Time to herd immunity (3,5) | 5.69 | 1.13 |
| 6 | Occurred side effects per manufacturer (6) | 5.67 | 1.35 |
| 7 | Occurred side effects (6) | 5.52 | 1,42 |
| 8 | Vaccination rate first vaccination (1) | 5.46 | 1.24 |
| 9 | Information on common but harmless vaccination reactions (9) | 5.43 | 1.44 |
| 10 | General vaccination willingness (5) | 5.40 | 1.32 |
| 11 | Progress by age group (2) | 5.34 | 1.17 |
| 12 | Absolute number of vaccinated people (1) | 5.23 | 1.41 |
| 13 | Vaccination progress by regions (within a country) (2) | 5.23 | 1.18 |
| 14 | Mechanism of respective vaccine (5,8) | 5.18 | 1.50 |
| 15 | Vaccination effects (calculation of how many deaths avoided etc.) (3,5) | 5.14 | 1.53 |
| [..] | [..] | [..] | [..] |
| 20 | Approved vaccines per country (4) | 4.26 | 1.73 |
| [..] | [..] | [..] | [..] |
| 31 | Vaccine orders (7) | 3.63 | 1.65 |
| 32 | Deliveries by receiving institution (7) | 3.64 | 1.51 |
| 33 | Deliveries by manufacturer (7) | 3.64 | 1.49 |
| 34 | Vaccination progress by education (2) | 3.44 | 1.67 |
| 35 | Vaccination progress by gender (2) | 3.33 | 1.58 |
| (1) total population, (2) population parts, (3) forecasts/calculations, (4) country comparisons, (5) additional information, (6) side effects, (7) deliveries, stock and orders, (8) own vaccination, (9) effectiveness | | | |

It should be noted, that the information relevance may be different for different stakeholders. For example, information about vaccination progress by region or education level enables policymakers to target vaccination campaigns more effectively. With regard to the previously stated categories, the free text field made it possible to identify a further information category, *extended rights* (10). The explanations of survey participants referred to freedoms regarding visits abroad, private meetings and stays in public locations. Further comments in the free text field referred to booster vaccinations and infections despite vaccination. Participants were also asked to indicate the likelihood of using the dashboard in specific situations on a 7-point Likert scale. The responses indicated that they would be more likely to use it before a vaccination decision (M = 5.10) than afterwards (M = 4.58).

### 5.3 Evaluation Cycle 3: Expert Interviews

Based on the dashboard analysis and the user survey, a click prototype was created. The main screen is displayed in Figure 3. Some subgraphs are based on analyzed dashboards, such as the German government and the Zeit dashboard. The categories with metrics assessed as highly important in the survey are displayed compactly and, by clicking, more context-related information of the respective category is shown. With the intuitive click option, we referred to DP1. Higher accessibility was achieved by incorporating choices such as the selection of different languages. By categorizing the

information and displaying the most important metrics on the main screen, DP2 was considered. It also became obvious that multiple data sources were needed (DP3).

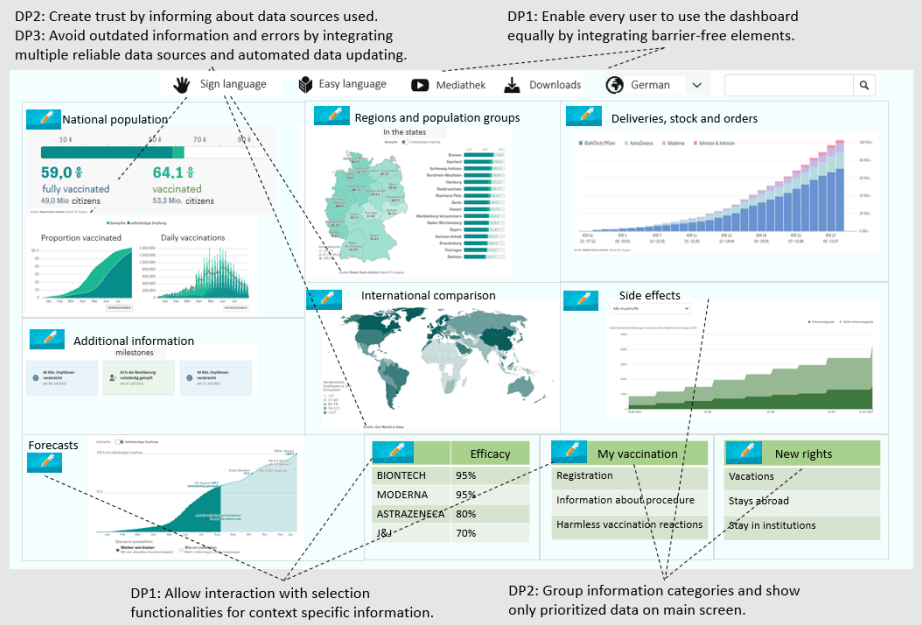


**Figure 3.** Vaccination dashboard main screen of the developed prototype

The prototype was introduced in five semi-structured expert interviews in July 2021. All interviewees evaluated it and performed a user test including tasks such as searching for vaccination rates in geographical regions. The experts have relevant experience as a data mining specialist (E1), data scientist (E2), and scientific researchers in digitization in healthcare (E3-E5). After the user test, DP1 was discussed regarding interactivity and further UI-aspects. Finally, the interviewees were asked about the technical deployment (DP3), in which they contributed their expert knowledge.

With regard to the UI, suggestions were made on the order of the information categories by pointing out that important metrics, such as the total vaccination rate, should be displayed first, while less dynamic information should be placed below (E2). A uniform presentation with a simple choice of colors was also emphasized, which was largely, but not optimally implemented in the click prototype (E3).

All interviewees favored interactive elements. However, E1 emphasized that the focus should be on presenting the most important information. The majority of the interviewees suggested filter functions in the form of drill-down elements (E2-E5). E4 concretized this by explaining: "[…] *that I can filter by month, that you can select the time frame, and then perhaps also make comparisons: for example, Germany and the Netherlands, or Germany in January and Germany in February*." Push notifications were not considered useful as they can be annoying (E3). E1 is also critical of push notifications, stating: *"You have to be careful with such alerts that you don't overinform people and it just grows tiresome."* E2 differentiated according to the device, stating

that it may be useful for a mobile app, but not for desktop use. Accordingly, he recommended responsive design integration (E2). E5 referred to the integration of barrier-free elements by stating that *"accessibility elements, such as easy language, language selection and plug-ins to read content aloud are very important to reach all segments of the population, especially those with handicaps."*

Regarding the technical development and ongoing provision, several data sources are necessary, which might be only available in a non-standardized or even unstructured way. E2 identified a challenge in this context, emphasizing obstacles in data scraping from different sources. According to E1, after a lot of initial development work, effort for the ongoing process of extract, transform and load (ETL) data can decrease. He described this with different date formats among data sources: *"Within a source, data format normally doesn't change. That means you once prepare for the differences between data sources at the beginning"* (E1). The data experts agreed that a database must be set up, which centrally stores the information from various databases (E1, E2).

## 6 Discussion, Limitations and Future Research

The aim of this study was to examine how vaccination dashboards should be designed to adequately meet user needs. Based on the literature and by adopting a DSR approach, we were able to identify potential Is, from which we derived eight MRs. We concluded three DPs, which we further analyzed and specified in three evaluation cycles. DP2 was a particular focus of our analysis, as it enabled us to analyze vaccination-dashboard-specific insights. The development of our prototype and its discussion in expert interviews provided insights into our implementation of the DPs.

With regard to **RQ1**: *Which information and metrics regarding COVID-19 vaccination are relevant to the vaccination dashboard users*?, **DP2** and the first two evaluation cycles played an essential role. With our evaluation process, we identified important metrics for COVID-19 vaccination dashboards by analyzing existing dashboards (cycle 1) and conducting an online survey (cycle 2) to analyze which information is especially important from a user's perspective. The total vaccination rate should be undoubtedly displayed on the main screen. Furthermore, the survey results convey that vaccination dashboards should contain information both on the efficacy of vaccines and on side effects, which was not fully implemented by the existing dashboards. We recommend to provide a personal decision support regarding vaccination, comparing the hospitalization rate due to side effects and breakthroughs with the hospitalization rate when vaccination is refused. Additionally, we categorized vaccination information into ten different groups. These categories as well as their most important metrics should be displayed on the main screen allowing further navigation. We emphasize that not too many metrics should be displayed on the main screen to avoid an information overload for the user.

Including these categories and metrics creates greater transparency. With regard to the COVID-19 vaccination, uncertainty is understandable, since the vaccines were novel in terms of their methodology and went through the approval process in a short time [7]. Skepticism and missing knowledge can be counteracted with purposeful

information provision on dashboards. Listing relevant information adequately can help people to make an informed vaccination decision. Those who have already been vaccinated can check whether occurring side effects are a serious problem or harmless. Even though vaccination dashboards are designed for the public, they can also be useful for governments. Policymakers can use the information on regional vaccination rates to decide where additional vaccination centers should be established or if vaccination campaigns should be initiated. Further adjustments for policymakers may include a macroeconomic cost-benefit comparison of the complex vaccination campaigns.

By referring to **RQ2**: *How should the determined important metrics be displayed on a user-centered vaccination dashboard with regard to the design and which technical issues need to be considered?,* **DP1** was considered in the evaluation cycles 1 and 3. By analyzing existing vaccination dashboards, we were able to derive insights into the UI. Various interactive elements were identified, and useful interactive elements were specified by the interviewed experts. In addition to simple click options for further information on individual information categories, filter options with drill-down menus should be implemented and the design should be moderate in terms of color choice, which is similar to findings in literature [5, 25]. Furthermore, information categories should be shown with a certain level of consistency, implying a mainly uniform selection of presentation forms. The provision of accessibility is essential and might be crucial for vaccination dashboards. Accessibility should especially include selection options for foreign languages and explanatory videos, in order not to neglect disadvantaged groups, which may have a lower vaccination rate. **DP3** was particularly considered in the interviews. It could be constituted that a central database should be set up in order to integrate the various data sources and to implement a well-considered ETL-process. Different data formats between individual data sources can be eliminated through initial standardization. Consequently, an increased automatization in the ongoing process of providing updated information can be achieved.

In the context of practice, the findings can be relevant to vaccination dashboard developers with regard to the content, design and technical challenges. From a scientific point of view, new insights regarding the design knowledge could be elaborated. The findings are not only relevant to COVID-19 vaccination campaigns including potential booster vaccinations, but also for vaccination dashboard development regarding other transmittable diseases and future pandemics. With respect to healthcare communication guidelines, such as those from the WHO, also emphasizing aspects such as accessibility, comprehensibility, timeliness, relevance and credibility (59), vaccination dashboards can contribute substantially to the management of pandemics.

Despite the findings, there are limitations to our research. First, we did not investigate in detail how to overcome the technical and process hurdles. In practice, problems of incompletely updated datasets became public, leading to a lower and incorrect official vaccination rate [60]. Second, our analyses were conducted at a time when most people in Germany had been vaccinated. The relevance of the metrics might depend on the status of the vaccination campaigns. For example, at the beginning of vaccination campaigns, information on supplies and stocks may be more relevant, as this is a bottleneck factor. Future research could analyze how the relevance of metrics on vaccination dashboards changes depending on the vaccination progress.

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