Mobile Crowd Sensing Services for Tinnitus Assessment, Therapy and Research

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***Abstract*—Tinnitus, the phantom sensation of sound, is a highly prevalent disorder that is difficult to treat; i.e., available treatments are only effective for patient subgroups. Sufficiently large and qualitative longitudinal data sets, which aggregate the individuals' demographic and clinical characteristics, together with their response to specific therapeutic interventions, would therefore facilitate evidence-based treatment suggestions for individual patients. Currently, clinical trials are the standard instrument for realizing evidence-based medicine. However, the related information gathering is limited. For example, clinical trials try to reduce the complexity of the individual case by generating homogeneous groups to obtain significant results. From the latter, individual treatment decisions are inferred. A complementary approach would be to assess the effect of specific interventions in large samples considering the individual peculiarity of each subject. This allows providing individualized treatment decisions. Recently, mobile crowd sensing emerged as an approach for collecting large and ecological valid datasets at rather low costs. By providing mobile crowd sensing services to large numbers of patients, large datasets can be gathered cheaply on a daily basis. In the *TrackYourTinnitus* project, we implemented a mobile crowd sensing platform to reveal new medical aspects on tinnitus and its treatment. Additionally, we work on mobile services exploring approaches for understanding tinnitus and for improving its diagnostic and therapeutic management. We present the *TrackYourTinnitus* platform as well as its goals, architecture and preliminary results. Overall, the platform and its mobile services offer promising perspectives for tinnitus research and treatment.**

***Keywords*-mobile crowd sensing, mobile healthcare application, tinnitus, tinnitus variablity, clinical trial**

I. Introduction

Tinnitus is a highly prevalent disorder (10-15 percent of the population reports tinnitus) that currently has no sufficient therapy [1]. Further, it is a purely subjective sensation that can only be assessed by the report of the individual patient. The pathophysiology of tinnitus is incompletely understood and clinical trials frequently reveal contradictory results. Presumably these non-conclusive results can be explained by the fact that tinnitus is not a homogeneous clinical entity. Instead, there exist many forms of tinnitus, being distinct in their clinical characteristics as well as response to specific therapeutic interventions [2]. Additional complexity is introduced by the fact that the perception of tinnitus loudness and distress is not constant in most cases, but varies over time depending on the context (e.g., environmental sound level or stress) [3].

These inhomogeneous samples and the variability over time provide an explanation for negative or non-replicable findings encountered in most clinical tinnitus trials. Best case, clinical trials can provide information on the efficacy and safety of one therapeutic intervention in the investigated sample. Furthermore, clinical trials generating such data have been cost- and labour-intensive. In addition, the procedure to involve and motivate patients is challenging and the investigated patient sample is often not representative due to restricted inclusion and exclusion criteria.

In order to mitigate these shortcomings, we developed a mobile crowd sensing [4] platform called *TrackYourTinnitus*[1](*TYT*). It tracks the individual tinnitus perception by a specific questionnaire developed by us to assess tinnitus perception and tinnitus-related parameters during the daily routine of a patient. Additionally, the smart mobile device of a patient records the environmental sound level while the patient fills out the assessment questionnaire. Results are transferred to the *TYT* backend, which, in turn, offers features enabling researchers to evaluate gathered patient data.

The remainder of this paper is organized as follows: Section II introduces the *TYT* platform and its main features. In Section III we discuss the current project status, whereas Section IV presents project results. Section V discusses mobile services built on top of the *TYT* platform. Section VI discusses related work and Section VII concludes the paper with a summary and outlook.

II. The TrackYourTinnitus Mobile Crowd Sensing Platform

Tinnitus is a purely subjective phenomenon that is difficult to measure. Moreover, tinnitus assessment is complicated by the fact that tinnitus awareness and loudness vary over time,

[1]Further information can be found at: https://www.trackyourtinnitus.org

depending on current activities, environmental sound, stress level, tiredness, and spontaneous fluctuations.

Magnetoencephalographic studies revealed that the magnitude of functional connectivity between the brain areas of the central auditory system and the ones responsible for conscious perception, differs between tinnitus patients and healthy controls [5], [6]. In turn, the intensity of this connectivity correlates well with the tinnitus-related distress reported by patients.

More recent research showed that the variability of oscillatory brain activity over time is reduced in the central auditory system of tinnitus patients compared to controls [7], which might influence the connectivity with the attentional brain networks as well. Further research is needed to evaluate in what way fluctuations of neuronal activity relate to the variability of the subjective tinnitus perception. In addition, for both diagnostic assessment of tinnitus patients and outcome measurements of therapeutic interventions, an exact assessment of an individual's tinnitus is important. However, in light of the variability of tinnitus loudness and awareness under real life conditions, a comprehensive assessment of tinnitus is challenging as well as cost- and labour-intensive.

The *TYT* mobile crowd sensing platform aims at measuring fluctuations of tinnitus perception and tinnitus distress under real life conditions during a patient's day as well as for large numbers of patients. This allows tracking the moment-to-moment fluctuation of the tinnitus. Furthermore, tracked data may be related to everyday behavior and the daily routine of patients to systematically identify relationships between individual routines and tinnitus fluctuations. Moreover, the *TYT* mobile crowd sensing platform can be used to assess the effects of specific standardized therapeutic interventions.

The *TYT mobile crowd sensing platform* has been developed in the context of a larger tinnitus database project[2] by a multidisciplinary research team consisting of psychologists, physicians and computer scientists. It comprises a website, a backend and two mobile applications (cf. Fig. 1). The latter track the individual tinnitus perception by providing three core features:

1) Patients have to fill out a questionnaire (cf. Fig. 1④) developed to assess tinnitus perception and tinnitus-related parameters during the daily routine of a patient. Thereby, patients are asked to complete the assessment questionnaires at different times during the day on a random basis (up to 12 notifications per day). This procedure ensures that patients cannot foresee the time of being asked and are involved in various daily situations. Only when applying such randomized approach, results might be of ecological validity.
2) In addition to the randomly applied questionnaire, for assessing momentary tinnitus loudness and distress, once, users have to fill out three standardized tinnitus questionnaires (cf. Fig. 1③) for the assessment of stable tinnitus characteristics. Users may process them with their smart mobile device or the website.
3) The smart mobile device records the environmental sound level by using the integrated microphone, while the patient fills out the assessment questionnaire. Results are stored on the smart mobile device and transferred to the *TYT* backend.

[2] TINNET; http://tinnet.tinnitusresearch.net/

Several other aspects had to be considered when developing the apps. These aspects are either relevant for meeting basic requirements of clinical practice (CP), for coping with the technical environment (TI), or for increasing user motivation (UM):

1) The questionnaires must run in the same way on all supported mobile operating systems (*CP*).
2) User privacy must be ensured through secure data transfer; produced data must be pseudonymized (*CP*).
3) It must be possible to build study groups (*CP*).
4) The *TYT* platform must ensure that the standardized questionnaires are completed by the user before starting the assessment based on the questionnaire. Note that a user may enter the platform via the app (cf. Fig. 1①) or the website (cf. Fig. 1②). Therefore, it must be ensured that the standardized questionnaires are completed in the same way using the app or the website (cf. Fig. 1③) (*CP*).
5) The schema to randomly apply the assessment questionnaire to a patient must be stored locally on the smart mobile device to be able to cope with long periods of disconnection. In addition, patients must be able to locally adapt the schema when the environment changes (e.g., the user being on holidays; cf. Fig. 1⑤). Further, the schema must be synchronized with the *TYT* backend, and the feature to adapt the schema must be provided in the same way on all mobile operating systems and on the website (*TI*).
6) Processed assessment questionnaires and recorded sound levels might produce large longitudinal data sets. Data must be locally cached on the smart mobile devices to cope with disconnections. Furthermore, it must be securely transfered to the *TYT* backend to prevent data loss as well as to ensure user privacy (*TI*).
7) As an incentive, patients should be enabled to interact with the *TYT* platform, e.g., to view the results of the assessment questionnaires. This feature must be provided on the smart mobile devices as well as on the *TYT* website (*UM*).

Table I summarizes current features of the platform.

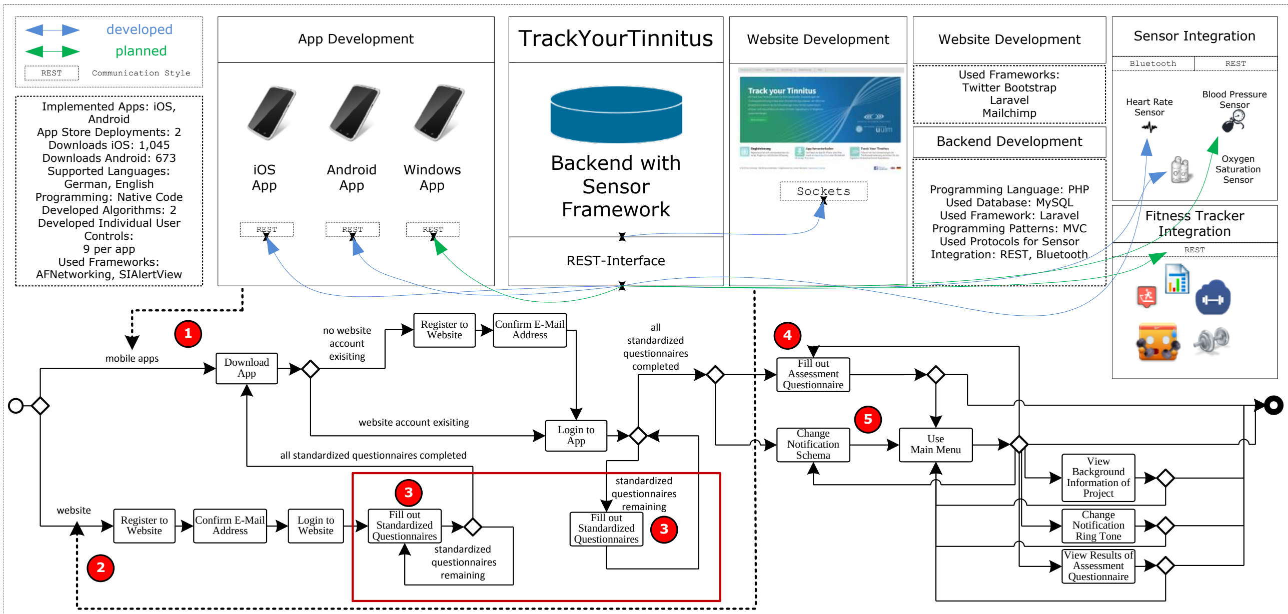

Figure 1: TrackYourTinnitus Platform

III. Project Status

Table II presents current project figures (April 2015). The project has been running for 12 months. We obtained 11,095 filled assessment questionnaires during this period, stemming from more than 800 international users. The number of users increases around 20 per week and hence, the number of assessment questionnaires increases. In the beginning, the *TYT* app and website were only provided in German language. After three months, an English version was added. Currently, we realize Spanish, French, Polish and Portuguese versions. Psychometric validation of questionnaires in these languages has shown that results are comparable [8].

We discuss some of the lessons learned made during the project in more detail: *First*, we learned that, in general, users are motivated to participate due to their health impairment. However, when considering the figures presented in Fig. 2, more incentives must be provided to increase user motivation. Most of the randomly answered assessment questionnaires were processed by only a small group of the registered users. We investigated all gathered data of this group and first results indicate that they suffer severely from their tinnitus.

Hence, at this early stage, the developed mobile crowd sensing platform has primarily attracted severely affected tinnitus patients. For motivating patients who are less severely impaired, additional features are needed to increase the overall benefit of the *TYT* app for patients. Currently, the major added value of the *TYT* app for the patient is the feedback on entered information. In order to increase user motivation, we are developing a toolbox with different features that may be helpful for reducing tinnitus perception and annoyance. Examples of such features are auditory stimulation, cognitive-behavioural therapy elements, social interactions, and specific games. Another approach to address user motivation will be to implement mechanisms enabling users to register displeasure about existing *TYT* features. Consequently, registered displeasure can be evaluated and may be addressed.

Second, we are developing an additional questionnaire to better understand why iOS is predominantly used.

Third, other research groups from the medical domain

Feature	Website	iOS	Android
Register for platform	√	√	√
Fill out standardized questionnaires	√	√	√
Fill out assessment questionnaire	–	√	√
Visualize results	√	√	√
Change notification schema	√	√	√
Build study groups	√	√	√

Table I: TrackYourTinnitus Features

Category	Value
Project start	4/2014
Registered users	822
User home countries	75
Reported problems and failures	10
Number of developed questionnaires	4
Programmers	1
Team size	5
Emerged requests for using platform	5
APP downloads iOS	1,045
APP downloads Android	673
Processed assessment questionnaires	11,095
Processed standardized questionnaires	1,583
Totally gathered answers	90,343

Table II: TrackYourTinnitus Figures

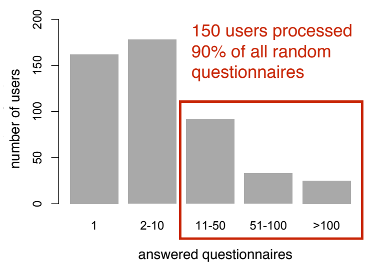

Figure 2: Assessment Questionnaires and User Activity

have encouraged us to realize features that allow customizing the platform to specific needs. For example, to change the questionnaires was often requested.

Fourth, we give insights into our expectations on the data we want to collect with the platform in future. Tinnitus is not the only prevalent disorder causing a large number of severely impaired patients. In the future, the platform will be applied in the context of other diseases as well. Its first use in practice indicates that it is feasible in the healthcare domain. In particular, it should be evolved to apply it in the context of clinical trials with the goal to increase ecological validity, while reducing costs at the same time. We expect that the data collected with the *TYT* app will provide new insights on the different subtypes of tinnitus.

Moreover, we expect that the amount of data collected with the platform will significantly grow for two reasons. *First*, we currently only provide German and English as platform languages. As mentioned, other languages will be added, which will result in a large number of additional users. *Second*, we are working on features that will motivate more registered users to process the assessment questionnaires. As shown in Fig. 2, 18% $(150/822)$ of the registerd users created the magnitude of the processed questionnaires (90%). Furthermore, if other research groups from the medical domain will largely collect data with the *TYT* platform, a large multi-centric as well as multinational data pool can be envisioned.

IV. Preliminary Results

This section presents preliminary results of the project. First of all, the goals are discussed from a technical (T) as well as a medical perspective (M) (cf. Table III). Then, the achievements in respect to three of these goals are presented in detail.

- T.Goal 1: An algorithm randomly notifying patients was required to ensure ecological validity. In particular, the algorithm behaves equally on all mobile operating systems supported (i.e., iOS and Android)—we could reach this goal by providing two different implementations to cope with the specific characteristics of the respective mobile operating systems.
- T.Goal 2: An offline mode must be supported as well. Consequently, data produced in offline mode must be cached—such caching was implemented. However, to also enable random notifications in offline mode, the specific characteristics of the two mobile operating systems need to be considered. While iOS offers a core feature to implement respective notifications, Android required us to implement it from scratch.
- T.Goal 5: A feature to view assessment results must be provided—we evaluated various approaches to ensure that user needs are met in the same way on both the smart mobile devices and the website.
- T.Goal 6: A data export feature is required, which has not been implemented yet. However, we add export interfaces that will enable patients to interact with their treating physician and allow clinicians to process data with statistical software.
- M.Goal 3: In noisy environments, the tinnitus might be partially or totally masked by surrounding sounds—in the *TYT* app, background noise levels are recorded in order to evaluate whether a reduction of tinnitus awareness is caused by masking sounds or other factors.
- M.Goal 4: Users must get access to personal data to learn more about their individual tinnitus. This will allow them to prevent behaviour worsening their tinnitus and to deliberately engage in behaviour leading to an improvement—we implemented respective features for visualizing and displaying patient data.
- M.Goal 6: Users enter sensitive medical data with the *TYT* app—to ensure privacy, all data gathered are anonymized. Furthermore, users may delete their account. Even if the account is deleted, data will be kept at any time to ensure that the clinical trial will not be manipulated—we implemented respective features to ensure that all gathered data are anonymized and clincial trials cannot be manipulated.

A. Notification Algorithm

We implemented an algorithm that applies the assessment questionnaire to registered users on a random basis. As a prerequisite, users have to specify a personal notification

Goals	Description
Technical Goals	
T.Goal 1	Develop notification algorithm.
T.Goal 2	Provide offline mode.
T.Goal 3	Provide similar mobile user interfaces.
T.Goal 4	Integrate website and apps properly.
T.Goal 5	Provide visualization of results.
T.Goal 6	Provide data export features.
Medical Goals	
M.Goal 1	Collect longitudinal data for assessing individual tinnitus fluctuation
M.Goal 2	Assess magnitude of tinnitus variability
M.Goal 3	Relate tinnitus perception to environmental noise
M.Goal 4	Provide feedback to patients
M.Goal 5	Evaluate crowd sensing for clinical trials
M.Goal 6	Ensure user privacy

Table III: TrackYourTinnitus Goals

schema when registering at the *TYT* platform (cf. Fig. 1⑤). This schema comprises the following user-specified aspects: First, the user must specify the number of notifications applied on a daily basis. Second, users must specify the days at which they want to be randomly notified; i.e., each user must specify the time window he or she wants to be randomly notified (e.g., Mondays between 2 and 6 p.m.).

The algorithm then uses the schema to calculate random notifications for the respective user. Note that notifications are realized based on the principle of local notifications; i.e., they can be performed on smart mobile devices without any connection to the *TYT* backend. Local notifications have become necessary to be able to cope with longer periods of disconnection. Due to the lack space, we omit details on how we implemented local notifications on iOS and Android.

The schema is used by the notification algorithm as follows:

1) The algorithm partitions the time window a user has specified with respect to a particular day into n time intervals of equal length. n corresponds to the number of notifications the user has chosen.
2) The algorithm then calculates exactly one notification for each interval. Thereby, it ensures that for each notification the points in time for each notification are randomly calculcated.
3) Finally, it is ensured that there are at least 15 minutes between two notifications.

We only present the algorithm running on iOS (cf. Algorithm 1) and the calculated notifications for a single day. In practice, notifications are calculated in advance.

Algorithm 1: iOS algorithm for daily notifications of a user

```
   Data:
   timeInterval: time interval a user has specified for a day
   numberOfNotificationsPerDay: notifications specified for a day
   Result:
   scheduleLocalNotification: calculated random notifications for a day
1  begin
2      lengthOfIntervall = timeInterval/numberOfNotificationsPerDay;
3      lastNotification = 900;                          /* the 15 minutes */
4      foreach n ∈ numberOfNotificationsPerDay do
5          secondsSinceStartOfInterval =
           arc4random_uniform³(lengthOfIntervall);
6          absoluteInterval=
7          secondsSinceStartOfInterval+(n*lengthOfIntervall);
           /* check the 15 minutes                                */
8          if absoluteInterval − lastNotification < 900 then
9              absoluteInterval = 2*absoluteInterval - lastNotification;
10         end
11         lastNotification = absoluteInterval;
           /* check if notification is in
              absoluteInterval                                    */
12         if absoluteInterval < timeInterval then
               /* notification found                              */
13             scheduleLocalNotification =
               scheduleLocalNotification ∪ absoluteInterval;
14         end
15     end
16 end
```

[3]arc4random_uniform(upper_bound): iOS internal function to return a uniformly distributed random number less than upper_bound.

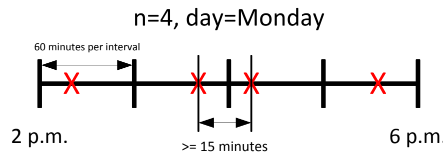

Figure 3: Example of Algorithm 1

Consider Line 12 of Algorithm 1. It may happen that a user is notified after the end of the time window specified by the user. These notifications are not considered for the $scheduleLocalNotification$ of a day and hence reduce $numberOfNotificationsPerDay$. The approach has proven its feasbility for practical as well as statistical use. Fig. 3 presents a computation example for Monday with a user-specified time window between 2 and 6 pm.

Altogether, we have not changed the algorithm since project start (4/2014). It has worked properly from a technical perspective (i.e., no problems were reported by *TYT* users). From a statistical perspective, more data is needed to fully evaluate the appropriateness of the algorithm in the large scale.

B. Assessment of the magnitude of tinnitus variability

Figures 4-6 present clinical data of individual patients we gathered with the *TYT* platform to assess and investigate the magnitude of tinnitus variability.

Fig. 4 shows data of a tinnitus patient with a large variability of the tinnitus loudness. The patient has answered almost 400 notifications using the mobile app. The variation of tinnitus loudness is shown on the ordinate.

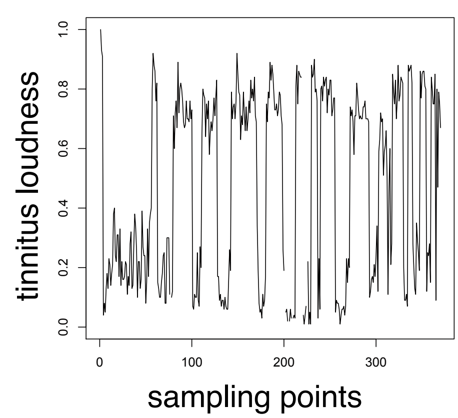

Figure 4: Tinnitus Perception and Large Variability

Fig. 5 shows data of a tinnitus patient with a strong relationship between tinnitus perception and the environmental sound level that was measured by the mobile *TYT* app when the patient was answering the assessment questionnaire. The measurements of the sound pressure level have been normalized (z-transformation). In quiet environments, the tinnitus loudness varied between 0.1 and 0.7. In turn, in loud environments the tinnitus was always suppressed to a level below 0.2.

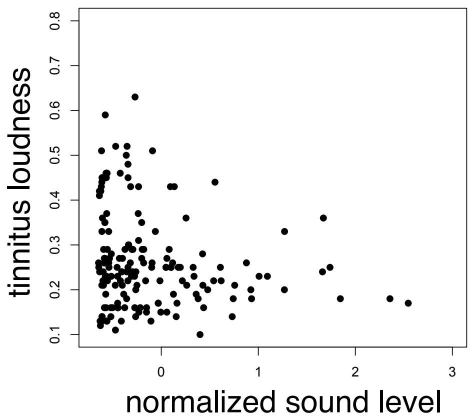

Figure 5: Tinnitus Perception and Environmental Sound Level

Finally, Fig. 6 shows data of a tinnitus patient with a clear relationship between the subjective perception of tinnitus and the time of day. The tinnitus loudness ratings were averaged for the hours from 8 am to 11 pm. In the morning, the patient perceives the tinnitus with reduced loudness. During the day, the perceived loudness of tinnitus increases up to its maximum at night.

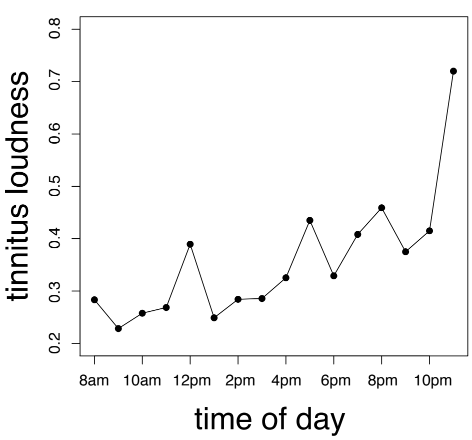

Figure 6: Tinnitus Perception and Time of Day

Altogether, first results have shown that the magnitude of the perceived tinnitus loudness can vary largely. This variation can be related to the sound pressure level of the surrounding environmental sounds or to the time of day. Other factors are currently under investigation. This variation of tinnitus perception may represent an important confounding factor for clinical trials.

C. *Evaluation of mobile crowd sensing for clinical trials*

Today, clinical trials usually measure the tinnitus loudness at one point in time before the start of the clinical intervention and at one point in time directly after finishing it. This routine, however, does not consider the variations of tinnitus loudness as measured with the *TYT* platform. In fact, the variation of tinnitus loudness can introduce a large variance in the data of the clinical trial that is not related to the clinical intervention per se. Based on this data, we suggest refining the standard protocols of clinical trials in the field of tinnitus by adding additional measurement points before and after the intervention for a better estimation of the true effect introduced by the clinical intervention. Note that the described mobile application enables such refinements.

V. Further Mobile Crowd Sensing Services

This section presents further mobile services related to the *TYT* platform (cf. Fig. 7). Their development has been driven by findings obtained when running the project over 12 months. Note that our vision is to utilize the findings of the *TYT* platform for enabling new diagnostic and therapeutic approaches. At the current project stage, we have already prototypically implemented the *Tinnitus Navigator* app, whereas the *TYT Feedback* app is in planning stage. Additionally, the *TYT* platform has been extended taking the gathered findings into account.

A. *Tinnitus Navigator*

Tinnitus Navigator is realized as a mobile application and will be connected to the same website as the *TYT* apps. The *Tinnitus Navigator* aims to assist treating physicians in the diagnostic and therapeutic management of a tinnitus patient. In particular, it will provide treatment suggestions based on a patient's individual clinical profile. Treatment suggestions, in turn, will be based on a growing database that incorporates treatment guidelines, data from clinical trials, and longitudinal data from the *TYT* mobile crowd sensing platform. Recommendations are continuously updated through feedback from the *Tinnitus Navigator*. This mechanism ensures that recommendations, which do not provide the expected results, are continuously refined. Currently, the first prototypes of the *Tinnitus Navigator* mobile app on Android and on iOS have been implemented to address interface requirements.

B. *TrackYourTinnitus Extensions*

Two additional features (cf. Fig. 7①,②) were developed for the *TYT* platform. They were motivated by user requests running the project. First, we developed a mobile service enabling patients to determine the individual tinnitus frequency on their own (cf. Fig. 7①). Utilizing this information, patients can establish a therapy with the practitioner or adjust a running one.

We integrated three sensors as shown in Fig. 1. Previous work suggests that the conscious perception of the phantom

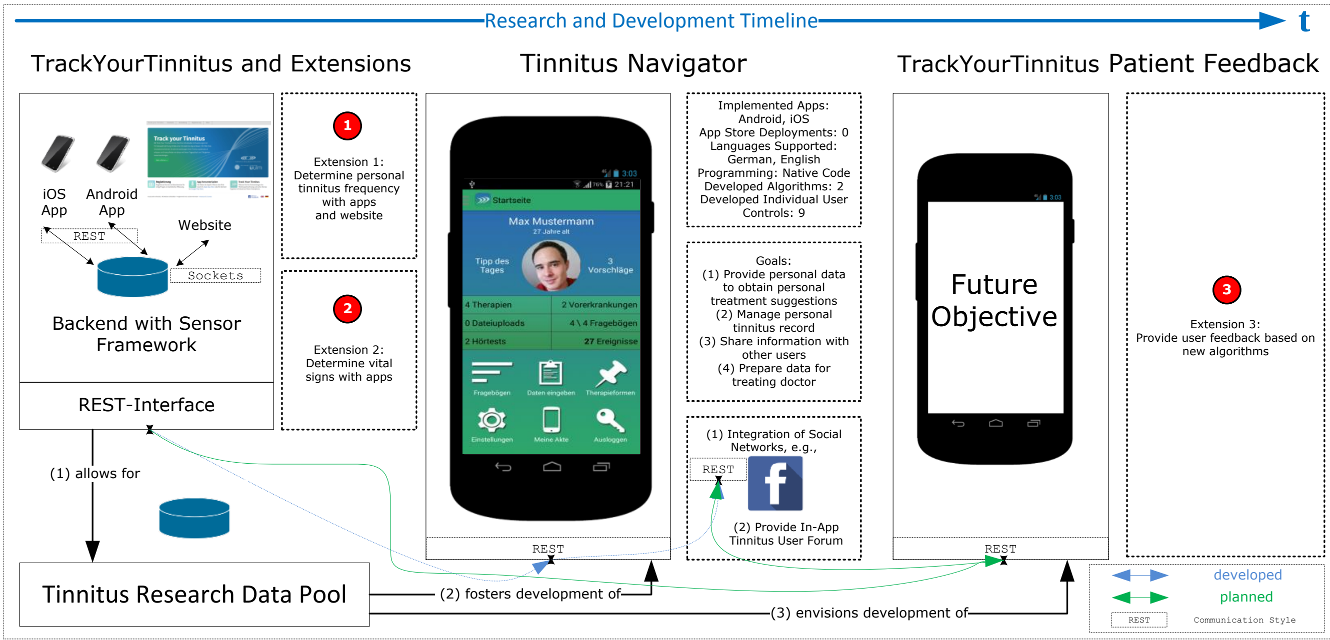

Figure 7: Mobile Services for Tinnitus Research and Treatment

tinnitus sound depends on more parameters than the recorded sound level. Others might be medication, emotional arousal, stress, alcohol, caffeine consumption, infections, hormone levels, rural versus urban environment, sleep quality, circadian and circaannual rhythm, or comorbidities. In order to collect more relevant contextual information, the three sensors were integrated to gather additional relevant data such as oxygen saturation or cardiac frequency. Thus, the mobile crowd sensing technology enables a detailed assessment of these parameters on tinnitus and annoyance. Note that a recent study has revealed the usefulness of large datasets for elucidating such relationships. The study analyzed Internet search engine query data to identify seasonal trends in tinnitus severity [9].

Currently, we are developing algorithms to automatically evaluate gathered patient data (cf. Fig. 7③). Either these algorithms calculate individual therapy suggestions for a patient or trigger other components being able to automatically refine therapy suggestions. Altogether, first experiments we made with the *TYT* platform revealed that intelligent feedback on collected data is essential for increasing the patient motivation to use the app.

VI. Related Work

Different categories of related work are relevant in the given context:

Approaches dealing with mobile crowd sensing [4], [10]–[12]. *First*, there are approaches that develop programming frameworks enabling users to easily configure mobile crowd sensing applications. For example, the framework presented in [12] enables users to configure such applications based on tasks, which can be specified in a high-level and user-friendly notation. To realize a collaborative learning application, tasks *Recruit, GetRawData, GetFeatures, and UploadFeatures* must be specified.

Second, there are approaches dealing with a specific mobile crowd sensing application scenario. For example, [11] utilizes Twitter for its mobile crowd sensing application. One of the applications presented in [11] evaluates recorded noise levels with the help of Twitter information. Thereby, smart mobile devices of many users automatically determine the local sound level and transfer recorded data to the Twitter platform. With this information, for example, it may be determined for a particular location whether a party is currently taking place. *Third*, there are approaches that investigate for which application scenarios mobile crowd sensing is useful [12].

Approaches utilizing mobile crowd sensing technology for clinical or psychological trials. Interestingly, mobile crowd sensing technology is still rarely used in a clinical context. This may be related to legal and data privacy issues [13], but also to a general resistance of health systems to adopt innovative data information technologies. Today, still the magnitude of clinical data is paper-based. However, it is expected that mobile and big data technologies [14], [15], with their potential to revolutionize clinical research and clinical trials, will enter the medical field.

Approaches that deal with mobile data collection based on psychological and clinical questionnaires. Recently, various mobile applications have been developed for psychological studies [16], [17]. In order to fully capitalize their potential, the pure adoption of existing questionnaires for mobile use will be outperformed by novel concepts for information collection [18], [19].

In summary, in many different life domains the feasibility of mobile crowd sensing has been already proven. The medical field, albeit a theoretically highly promising application for crowd sensing approaches, seems to be still neglected.

VII. Outlook and Summary

This paper introduced the *TYT* mobile crowd sensing platform. We presented the current status of its implementation and practical use. Furthermore, we discussed preliminary results we obtained when running the platform for over 12 months. In particular, we showed that these results indicate new insights on the tinnitus variability. We further showed that the obtained results provide the basis to develop new mobile crowd sensing services fostering tinnitus assessment, therapy and research. Moreover, the results indicate that users are actually motivated to use the platform, especially those severely suffering from tinnitus. Still more incentives and features are required to increase user motivation and hence to gather more valuable data on the tinnitus disease. Therefore, we are working on algorithms to automatically evaluate patient data in order to provide immediate valuable feedback to them. Altogether, using mobile crowd sensing and its application offers promising perspectives for tinnitus assessment, therapy and research as well as for the medical field in general.

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