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Empirical challenges in assessing the "leaky STEM pipeline": how the research design affects the measurement of women's underrepresentation in STEM

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Abstract

Background Despite a well-documented underrepresentation of women in STEM majors and occupations, empirical evidence on whether there really is a "leaky STEM pipeline" is mixed due to a lack of methodological consistency. Studies vary by (1) the definition of STEM, (2) the decision to measure choices alone or to also include aspirations, and (3) the use of longitudinal or cross-sectional data.

Results In order to analyze how variations in the research design affect the measurement of women's underrepresentation in the field of STEM, we critically reviewed relevant literature on the "leaky pipeline" and identified three central features in the designs of existing empirical studies. We illustrate how the variation of these affects the results by applying them to the German context. Our results support the "leakage" perspective for Germany only during the transition to the labor market. Changes in STEM aspirations between grades 9 and 12 do not follow a clear pattern. Indeed, a comparison of grade 12 aspirations to actual college major choices even shows an increasing share of women in STEM.

Conclusion Germany does not exhibit a significant "leaky STEM pipeline". Due to more men choosing STEM, gender gaps widen in higher education, while the pipeline remains stable. Therefore, we challenge the "leaky pipeline" metaphor, advocating a life-course perspective to better understand STEM trajectories. We call for refined measurement standards, emphasizing official STEM definitions, long-term observations from aspirations to career entry, and the use of longitudinal data.

Keywords Education, Gender segregation, Germany, Research design, STEM, Leaky pipeline

JEL Classification I240 Education and Inequality, J440 Professional Labor Markets, Occupational Licensing

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Introduction

The underrepresentation of women in STEM (science, technology, engineering, and mathematics) college majors and occupations has been discussed in sociological research for decades. Even though, today, women are more successful in higher education than men across the OECD (Buchmann & DiPrete, 2006; OECD, 2022, p. 218), they continue to choose different majors and occupations than their male peers. Across OECD countries, only 31% of 2020 entrants at the Bachelor level in the field of STEM were women (OECD, 2022, p. 186), while they continue to be overrepresented in humanities, education, and health majors (Barone, 2011; Mann & DiPrete, 2013; OECD, 2022, p. 189). Moreover, women are more likely to leave STEM programs in the course of higher education than their male fellow students (OECD, 2022, p. 207).

Female underrepresentation in STEM majors and occupations has been problematized by policymakers and researchers for three reasons: first, from an equity perspective, it is important to ensure that individuals can choose the subjects or occupations that appeal to them, without being discouraged by social perceptions of gender-typical fields (OECD, 2017); second, since STEM majors and occupations are associated with higher wages (Beede et al., 2011; Olitsky, 2014), the persistent gender gap in STEM fields contributes to earnings differentials between men and women, thus, accumulating over the life-course and leading to lower pensions and wealth for women (Blackburn, 2017; Council of the European Union Brussels, 2017) and third, against the background of an already existing and growing shortage of STEM professionals in the labor market, it seems reasonable to encourage women's participation in the field of STEM (Carnevale et al., 2020; European Commission, 2020).

But how does the female underrepresentation in STEM majors and occupations come about? Graduating from a STEM major marks the end of a process of occupational preference formation, which starts in childhood and continues through early adulthood. Stereotypical occupational preferences are internalized during childhood (Marini & Brinton, 1984; Okamoto & England, 1999) and stabilize until around age 14 for boys and only a little later for girls (Gottfredson, 1981; Schoon, 2001). Thus, gender-typical socialization processes steer boys towards and girls away from STEM occupations. In order to describe the declining share of women over their educational and occupational careers, Berryman (1983) established the term "educational pipeline" for examining students' persistence and retention across educational careers and for the comparison between subgroups (Berryman, 1983, p. 51). The so-called "leaky STEM pipeline" describes how the share of young women and men in STEM develops over the educational career, identifying a comparatively higher "leakage" of women out of the pipeline. Numerous authors have used the pipeline metaphor to examine the circumstances under which (young) women's and men's occupational aspirations and school course selections lead to college major choices and jobs in STEM fields (or not) (Alper, 1993; Hinton et al., 2020; Maltese & Tai, 2011).

However, the STEM pipeline metaphor has faced several criticisms. Linguistically, the metaphor has been criticized for portraying the STEM field as a predefined pipeline without reflecting its social, cultural and historical embeddedness, and for highlighting structural features that cannot be influenced by the individual (Tajmel, 2019). Conceptually, the pipeline metaphor implies a predefined set of education and employment stages that comprise a STEM career, with women dropping out at each stage. As a consequence, empirical research mainly focussed on gender differences at these drop-out points rather than investigating the complex pathways into STEM and the persistence therein (Xie & Shauman, 2003). Therefore, empirically, the metaphor fails to capture the diversity of individuals' pathways through STEM education and careers (Cannady et al., 2014; Miller & Wai, 2015; Nitzan-Tamar & Kohen, 2022). The metaphor oversimplifies and overlooks the complexity of education and employment pathways into STEM, where movement in and out of the STEM field occurs at various time points. This potentially leads to inaccurate policy implications and therefore calls for a broader perspective on STEM careers (Sevilla et al., 2023; Xie & Shauman, 2003).

Purpose of the study and research questions

We add to this critical literature by discussing challenges when empirically measuring the leaky STEM pipeline. Our starting point is the observation that previous studies differ substantially in the research design they apply, leading to variations in the size of the gender gap in STEM and in the magnitude of the leakage out of the pipeline. Therefore, the first aim of this paper is to review these variations in research designs by referring to previous literature and empirical analyses. Moreover, previous studies have hardly ever applied various measurements when investigating the leaky STEM pipeline (at least not at the time of publication). Therefore, the second aim of this paper is to empirically assess the consequences of design variations on measuring a potential leaky STEM pipeline.

We do this using the case of Germany, a country characterized by a strong link between higher education and the labor market (Leuze, 2010). So far, a large share of the research on the "leaky STEM pipeline" has been conducted in the US context (Filer, 2009; Maltese & Tai, 2011; Morgan et al., 2013; Weeden et al., 2020), while less is known about possible leakage patterns in continental Europe. Germany is an interesting empirical case for comparison with the US due to its high degree of occupational specificity and school tracking (Allmendinger, 1989; Kerckhoff, 1995). Regarding occupational specificity, Germany's labor market is characterized by strong occupational boundaries and a tight linkage to the education system, making occupational choices much more consequential than in labor markets that are less structured along occupations, such as that of the US (Kerckhoff, 1995). Concerning school tracking, Germany is characterized by an early assignment to the academic track in secondary school, with few options for track changes later on (Allmendinger, 1989), hindering a considerable proportion of adolescents from entering the (largely academic) STEM majors in higher education. Accordingly, the strong degree of occupational specificity and school tracking makes it more difficult in countries like Germany to enter the STEM pipeline and later changes therein (Marginson et al., 2013). Therefore, our paper not only demonstrates how the research design affects the measurement of the leaky STEM pipeline, but also provides empirical evidence on whether there is a leaky STEM pipeline in Germany.

However, it is important to note that our perspective on the leaky STEM pipeline is mainly descriptive, i.e., describing women's and men's pathways into and out of STEM, rather than seeking to explain why this is the case. There are numerous theoretical perspectives and concepts in research on the gender gap in STEM that aim to explain *why* women and men initially choose different majors and occupations or drop out of STEM, such as science stereotypes (Eagly, 2004; Miller et al., 2015), people vs. things orientation (Diekman et al., 2010; Su et al., 2009), gender-specific self-efficacy beliefs (Bandura, 1978; Eccles, 1987), academic self-concept (Ertl et al., 2017), social cognitive career theory (Lent et al., 2000), or sense of belonging (Cheryan et al., 2017). However, since our focus is on the research design applied when measuring the STEM pipeline, we cannot derive conclusions from these theories. Hence, we do not contribute to explaining women's underrepresentation in STEM. Instead, we show that variations in the research design affect the measurement of the "leaky STEM pipeline". Thus, we address the following research questions:

(RQ1) How does the exact definition of the subjects and occupations that are considered to be STEM affect the results about the gender gap in STEM at various stages of the STEM career?

(RQ2) How does the decision to include or exclude STEM aspirations in earlier educational stages in addition to STEM decisions affect the results about the gender gap in STEM?

(RQ3) How does the decision to use cross-sectional or longitudinal data affect the measurement of the "leaky STEM pipeline"?

Recently, a sensitivity to some of these aspects has been developed, mostly regarding the definition of STEM (Morgan et al., 2013; Weeden et al., 2020; Xie et al., 2015) and to a lesser extent the two other issues (for an exception see Cannady et al. (2014) or Mann and DiPrete (2013)). However, a joint discussion on how these design variations influence the measurement of the leaky STEM pipeline is still missing in the literature. Our analysis aims to close this research gap by not only discussing these issues based on previous literature, but also by providing empirical evidence on how these seemingly technical design decisions influence the substantial findings on the leaky STEM pipeline.

Challenges in measuring the "leaky STEM pipeline"

In the following, we will demonstrate research design variations of previous studies on the leaky STEM pipeline, resulting in variations in the size of the gender gap, in the magnitude of the leakage, and when it occurs over the educational career. We argue that possible variations depend on three factors: (1) the exact definition of which subjects and occupations are regarded as STEM and how they are measured; (2) whether the analysis only includes choices, or whether it also includes aspirations regarding STEM subjects and occupations; and (3) whether studies are based on pooled cross-sectional or longitudinal data. The first two points specify *what* is measured, while the last point specifies *how* the pipeline is measured.

Defining WHAT is measured: STEM subjects and occupations

To empirically measure the leaky STEM pipeline—that is, the share of women in STEM fields and occupations across the various educational and occupational trajectories—researchers first need to clarify their definition of STEM. While it seems evident that STEM refers to the areas of science, technology, engineering, and mathematics (Breiner et al., 2012), studies differ in terms of the subjects and occupations included in these broad categories, as well as in what they actually mean by this acronym (Banerjee et al., 2024; Oleson et al., 2014).

To start with, studies draw on different *classification systems* to identify STEM majors and occupations. Very few empirical studies on the leaky STEM pipeline use international classifications, such as the ISCED-F 2013 to code fields of study or the ISCO-08 coding for occupations (exceptions are; Barone, (2011) and Barone and Assirelli, (2020) for Italy; Sikora, (2019) and Law, (2018) for Australia and van der Vleuten et al. (2019) for the Netherlands). The vast majority of studies use country-specific coding systems to classify STEM domains. For the US, researchers often apply the Classification of Instructional Programs (CIP) to classify STEM majors (Mann & DiPrete, 2013; Morgan et al., 2013; Tyson et al., 2007), the Standard Occupational System (SOC) to classify STEM occupations (Bagnoli et al., 2014; Weeden et al., 2020), or codes from the O-Net database (Lauermann et al., 2017; Wegemer & Eccles, 2019). The few studies on the German context mostly apply the field of study classification issued by the German Federal Statistical Office (Hübner et al., 2017; Keyserlingk et al., 2020) and the German *Klassifikation der Berufe* (classification of occupations, KldB) (Jacob et al., 2020). Using country-specific classifications to define STEM majors or occupations has an advantage as they are tailored to local educational systems and labor markets. However, due to different national classification systems, results on the gender gap in STEM are not comparable across countries. Therefore, applying an international classification when defining STEM majors or occupations increases the cross-country comparability of the leaky STEM pipeline.

In addition to the chosen classification, the available *level of measurement precision* of the occupational classification has an important impact on the measurement of gender segregation in STEM. Since more aggregated classifications merge heterogeneous occupations and subjects, they conceal possible within-variations in certain categories (e.g., an over-representation of women in biology within the more gender-balanced natural sciences) or assign STEM-related occupations to non-STEM occupations on an aggregate level (e.g., assigning physics teachers to the general group of teachers) (Barone, 2011). Moreover, the conception of new and interdisciplinary majors (e.g., data science degrees with a mixture of social science and information technology) complicates assignment to a more aggregate subject category. Accordingly, using less aggregate versions of classification systems provides more precise measures of gender imbalances within these categories and results in higher levels of gender segregation (Smyth & Steinmetz, 2008).

Based on the chosen classification and the available level of aggregation, researchers must define which *majors and occupations are included in the STEM category*. They can either use existing definitions of STEM issued by political institutions or international organizations, or apply a self-developed STEM definition. Most researchers decide their own definitions of STEM majors or occupations, with some even creating new acronyms (like SET—science, engineering, and technology: see Bagnoli et al. (2014) or Bennett (2011); or SMET—science, mathematics, engineering, and technology: see Zhao et al. (2005)). When researchers use self-developed STEM definitions, they mostly rely on broad categories of mathematics, science, engineering, and technology, including STEM core fields and occupations (Xu, 2017). Some studies, however, also use more refined categories in their definitions. For example, including only physics, chemistry, or biology rather than sciences in general, or including computer science rather than the broad field of technology (Maltese & Tai, 2011) or taking math interest, achievement and calculus courses as a proxy measurement for STEM in general (Butler-Barnes et al., 2021; Chang et al., 2023). Other studies employ a broader STEM definition including medicine, health sciences, social sciences, or humanities (Andersen & Ward, 2014; Crain & Webber, 2021; Stets et al., 2017). Therefore, when researchers apply their own STEM definition, it is hardly possible to compare the empirical findings on the gender gap in STEM across studies.

Accordingly, we recommend using existing definitions of STEM issued by political institutions or international organizations. However, as argued by Manly et al. (2018), only a very small proportion of existing studies on the leaky STEM pipeline actually apply STEM definitions provided by official bodies. For example, the European Commission (EU Skills Panorama, 2014, p. 1) limits the STEM workforce to "people with a tertiary-education level degree in the subjects of science, technology, engineering and math" [this corresponds to "STEM-Core" in the discussion of Baum et al., (2015, p. 32)]. The EU definition is similar to the OECD definition (OECD & Eurostat, 1995). In contrast, major US classifications, such as those proposed by the U.S. Census Bureau or by the Standard Occupational Classification Policy Committee (SOCPC), apply a broader definition and include social science as a STEM field (Landivar, 2013).[1] Moreover, these US definitions further differentiate between STEM and STEM-related occupations, with the latter also including health and architecture (Landivar, 2013; Oleson et al., 2014). Generally, the underrepresentation of women occurs in STEM core fields and including social sciences in the STEM definition reduces the gender imbalance. If STEM fields even include health professions, gender integration may be reached (Baum et al., 2015). Lastly, some studies further disaggregate STEM subjects into those dominated by men (e.g., engineering, technology) and those with a more gender-balanced distribution (e.g., biology, architecture) (King, 2016; Mann & DiPrete, 2013). In doing so, they allow us to disentangle the overly broad category of STEM subjects and occupations.

Overall, different definitions of STEM are a major source of variation when defining the STEM pipeline and when measuring gender imbalances therein. Most previous studies (1) used national classification systems when defining STEM, without providing conversions to

[1] However, even two of the most commonly used US STEM definitions—the first issued by the National Science Board National Science Board (2014, chap. 3, p. 8) and the second issued by the National Center for Education Statistics (NCES) (see Chen and Weko, 2009)—vary considerably regarding the included occupations (see Oleson et al., 2014). Differences are mostly related to the inclusion of healthcare and managerial occupations as well as subgroups of social sciences. Accordingly, Oleson et al. (2014) show that the number of STEM jobs in the United States vary between 5.4 and 26 million people, depending on the STEM definition applied.

comparable international classifications; (2) applied a high level of aggregation within the classifications system, which obscures possible variations in the gender composition within subfields; and (3) defined STEM based on self-developed coding schemes rather than on definitions provided by official bodies. Due to these design decisions, the resulting empirical gender gaps in STEM are not comparable across studies, but rather a result of WHAT is measured. By taking our criticisms into account, researchers ensure international comparability and transparency of research.

Defining WHAT is measured: STEM choices versus STEM aspirations

The second important decision that needs to be made when measuring the leaky STEM pipeline is whether to include only *choices* (of subjects and occupations), or also to include prior occupational or subject *aspirations* in the analysis. While choices measure the concrete decisions made by individuals during their educational career, aspirations provide information about subjective individual desires to attain future educational or labor market outcomes. Regarding the STEM pipeline, choices relate, on the one hand, to choosing (advanced) STEM courses during school, selecting STEM majors in higher education, or working in STEM occupations thereafter. On the other hand, choices also refer to persistence in, or attrition from, STEM—namely, whether a student decides to stay in their originally chosen STEM major or change their subject to a non-STEM field. In contrast, aspirations developed during childhood and adolescence measure whether girls and boys aspire to study a STEM subject or to work in a STEM occupation later on. They are measured mostly during secondary schooling and before actual choices for or against STEM have been made. Thus, when looking at the STEM pipeline over a longer period of the life course, a combination of aspirations at earlier stages in school and choices at later stages in higher education and the labor market allows for a wider window of observation.

The largest proportion of research on the leaky STEM pipeline concentrates on gender differences in actual STEM choices. Previous studies consistently report that young men are more likely to choose STEM courses in secondary school than young women (Burkam & Lee, 2003; Filer, 2009; Jonsson, 1999), to enroll in a STEM major in higher education (Jacob et al., 2020; Mann & DiPrete, 2013; van der Vleuten et al., 2019), to graduate from a STEM major (Ma & Liu, 2017; Nix & Perez-Felkner, 2019; Riegle-Crumb et al., 2012), and to work in STEM occupations after graduation (Lawson et al., 2015; Sassler et al., 2017; Wang et al., 2013). Thus, focusing on decisions for or against STEM along the educational trajectory immediately reveals lower shares of (young) women in the STEM pipeline.

However, once individuals have entered the STEM pipeline, findings on gender differences in the persistence in, or attrition from, STEM majors are less conclusive. While some studies show a higher leakage of women throughout the STEM pipeline (Weeden et al., 2020), others report either more mixed results (Chen & Soldner, 2013), no disproportionate attrition of women (Chen & Weko, 2009; King, 2016; Maltese & Tai, 2011), or even higher persistence rates for women compared to men once they enter a STEM field in college (Ma & Liu, 2017). Moreover, gender gaps also differ within the broader STEM field, linking to the discussion regarding how to define STEM. While Weeden et al. (2020) find that women leak more often from the broad STEM category than men but not from health sciences, Sassler et al. (2017) show a higher leakage of women in computer science and engineering but not for all STEM domains. Accordingly, results on persistence in, or attrition from, STEM after making the initial decision to enter the STEM pipeline are more inconsistent and do not indicate a clear leakage of women out of the pipeline.

Even more variation is found when scrutinizing gender differences in STEM aspirations. Some studies focus on *idealistic* occupational aspirations (Bodnar et al., 2020; Frome et al., 2006), which are understood as students' "judgements of suitability or preference" (Gottfredson & Lapan, 1997, p. 430), irrespective of whether the individual can actually enter a specific career. In contrast, *realistic* occupational aspirations (also often called occupational expectations) are defined as students' stable prefigurative orientations composed of their specific beliefs about where their future trajectory will take them through the educational system and on to their ultimate occupational position (Gottfredson & Lapan, 1997, p. 430; Morgan, 2007, p. 1528).

Studies measuring gender differences in realistic STEM aspirations cross-sectionally (as is often done with Programme for International Student Assessment (PISA) data) generally agree that, across countries, young women aspire to STEM occupations less frequently than young men (e.g., Hägglund & Leuze, 2021 and Sikora & Pokropek, 2012). However, empirical evidence on gender differences in STEM aspirations is more mixed regarding the development of aspirations over the educational career. For the US, Saw et al. (2018) report a greater decrease in realistic STEM aspirations for girls than for boys between grades 9 and 11, while Barth and Masters (2020) find stable interest in mathematics and science throughout secondary school for girls and increasing interest for boys. For Flanders in Belgium, Ardies et al. (2015) find a decline in realistic STEM aspirations between grades 1 and 2 of secondary school for both girls and boys. For Sweden, Raabe et al. (2019) report a substantial decline in girls' preferences for STEM subjects between grade 8 and 9, but not for boys. Thus, empirical studies on the development of STEM aspirations in secondary education do not consistently report leakage of girls out of the pipeline but rather fluctuating patterns.

Very few studies combine both perspectives—aspirations and choices—and examine these concepts together (Bagnoli et al. (2014) for United Kingdom; Sikora (2019) for Australia; Wegemer & Eccles (2019) for the United States). From a life-course perspective, both concepts are related since STEM aspirations in secondary school have been found to be important predictors of STEM choices in higher education, at least in the US (Legewie & DiPrete, 2014; Morgan et al., 2013; Weeden et al., 2020), the UK (Schoon et al., 2007), and Australia (Law, 2018; Sikora, 2019). However, whether aspirations predict choices differs between men and women. According to Bagnoli et al. (2014), early SET aspirations in the UK only predict men's occupational outcomes, but not women's. Moreover, Schoon (2001) showed that aspirations in UK secondary schools are a better predictor of working in healthcare occupations compared to working in science and even less so in engineering occupations. Quadlin et al. (2021) found that men and women differ in how they translate the same aspirations into major choices, with men's major choices being more closely tied to prospective earnings than women's.

Consequently, analyzing aspirations and choices together allows researchers to scrutinize possible ways in and out of the leaky STEM pipeline more thoroughly than focusing on one aspect alone. By looking at aspirations in addition to choices, it is possible to understand gendered pathways into the STEM pipeline prevalent early during secondary school. Once decisions for STEM majors are made, focusing on drop-out choices allows researchers to investigate persistence in and retention in the STEM pipeline. Moreover, cross-national differences might stem from the relation between STEM aspirations and choices. In countries with strong occupational boundaries, such as Germany, STEM aspirations might be more important for later decisions than in systems that are less structured along occupational lines, like the US. Thus, combining aspirations and choices is thus necessary to gain a deeper understanding of how young men and women transition into and out of the STEM pipeline from adolescence to early adulthood.

Defining HOW it is measured: using cross-sectional or longitudinal data

While the definition of STEM affects the gender imbalance within the leaky pipeline, measuring the leakage process also depends on the type of data used, namely longitudinal or cross-sectional data. Both data types can be combined with measures of aspirations and choices. In other words, the concepts measured are not predetermined by the type of data used.

Researchers using cross-sectional data often apply a pooled cross-sectional design, for example, combining cross-sectional data on aspirations with cross-sectional data on major choices in higher education or subsequent occupational choices. Many studies based on (pooled) cross-sectional data have shown a stereotypical pipeline with a continuous decline in women's interest in and choices of STEM subjects and occupations (Alper, 1993; Contini et al., 2017; Ellis et al., 2016). In their meta-analysis for the UK, Tripney et al. (2010) have found that studies on STEM trajectories in school are mostly based on cross-sectional data.

The advantage of using pooled cross-sections is a larger number of cases per observed time point in the educational career. However, there are more drawbacks related to their use. First, there may be inconsistencies between the definition of STEM for each cross-sectional dataset and its operationalizations. Second, since data are collected from different sources and contain individuals of different age groups, results might be biased by a lack of comparability in terms of sampling design and sampling population. Third, possible leakage points in the trajectory might be overlooked or misinterpreted by relying on cross-sectional analysis. Since the samples of cross-sections are often not comparable, students with STEM aspirations might not be the same as students choosing STEM in higher education or working in STEM.

Consequently, following the same individuals longitudinally over their educational and occupational careers seems more appropriate when measuring the leaky STEM pipeline. Again, longitudinal data might contain a combination of both aspirations and choices for STEM, or only one of these concepts. The larger body of literature about women's underrepresentation in STEM written in the last decade is based on large-scale longitudinal data rather than on cross-sectional data. Again, most of these studies focus on the US (Legewie & DiPrete, 2014; Morgan et al., 2013; Weeden et al., 2020; Wegemer & Eccles, 2019), while fewer studies investigate the situation in European countries (Bagnoli et al., 2014 for the UK; Herbaut & Barone, 2021 for France; Schoon, 2001 for the UK; Vooren et al., 2022 for the Netherlands), South American countries (Sevilla et al., 2023 for Chile) or countries in the Middle East (Nitzan-Tamar & Kohen, 2022 for Israel), where adequate and representative longitudinal data for the measurement of the leaky STEM pipeline have only recently become available. In contrast to research relying on pooled cross-sectional designs, studies using longitudinal data show less consistent results for (young) women leaking out of the STEM pipeline. While some studies find a leakage only during the transition from secondary school to higher education but no gender differences in the persistence thereafter (Legewie & DiPrete, 2014; Sevilla et al., 2023), others show a more constant proportion of women transitioning into STEM fields from upper secondary level to higher education (Herbaut & Barone, 2021), and sometimes even an increasing share of women (Wegemer & Eccles, 2019).

However, studies based on longitudinal data also face methodological problems. The first issue is panel attrition—the selectivity caused in later waves by recruited panelists who cease to participate in the longitudinal survey, often not at random, leading to selectivity problems in the remaining sample. Second, to deal with this problem, panel-based studies are often balanced by participants who have taken part in all survey waves (Bagnoli et al., 2014), potentially resulting in a relatively low number of observations in STEM fields, especially for girls. For example, in the study by Wegemer and Eccles (2019, p. 32), creating STEM-only subsamples combined with attrition across waves sometimes leads to fewer than 10 observations per gender in the STEM-relevant categories. Third, there is a lack of longitudinal administrative data, that might help avoid panel attrition, as Nitzan-Tamar and Kohen (2022) did for Israel. Unfortunately, such data do not exist for many countries and does not contain information on, for example aspirations or explanatory variables for non-descriptive studies.

For this reason, it seems advantageous to compare cross-sectional and longitudinal findings of survey data, as done by Wegemer and Eccles (2019). When looking at cross-sectional gender ratios in STEM, they found a slightly increasing share of women in the fields of mathematics, physics, engineering, and computer science. However, their longitudinal analysis showed that more women and men switched in and out of STEM subjects between grade 7 and age 26 than the cross-sectional findings suggest. Legewie and DiPrete (2014) present similar findings for the development of STEM orientations between grades 8 and 12. When analyzing cross-sectional data, the relative number of STEM-oriented girls even rose, while their longitudinal analysis of transition rates shows a higher leakage of girls compared to boys into non-STEM fields.

Overall, we conclude that the application of longitudinal panel data following the same individuals over their educational careers is better suited to measure the leaky STEM pipeline than a pooled cross-sectional design. However, the related problems of panel mortality and small samples must be taken seriously since they might lead to biased estimates for a highly selective sample. Although the aim of studies on the leaky STEM pipeline should be to avoid both overestimation and underestimation of the phenomenon, the selected samples are rarely checked for their representativeness. This would mean, on the one hand, to check survey data for plausibility with regard to selection errors and response behavior, and, on the other hand, avoiding possible cohort effects or ecological fallacy of aggregates when using cross-sectional data. A comparison and harmonization of both designs allows taking advantage of both, the large case numbers in cross-sectional studies and the intraindividual perspective of survey-based panels.

Method

The German case study: data and classifications

We have shown in the previous sections that studies on the leaky STEM pipeline mainly differ from each other in three aspects: (1) how they define the STEM field, (2) whether the analyses include choices or aspirations, and (3) whether studies are based on cross-sectional or longitudinal data. In the following, we will empirically investigate the impact of those research design variations on the gender gap in STEM at different education and employment stages for the case of Germany. Such an investigation allows us to establish whether we can speak of a "leaky STEM pipeline" in Germany, as in other country contexts. Our analyses are based on a variety of datasets that provide representative information for an exceptionally long period of time. We start with students' realistic occupational aspirations in grade 9 and trace how they develop during secondary school up to grade 12. Next, we examine major choices when enrolling in higher education and follow students until their graduation.[2] Finally, we look at the first occupational placement after leaving higher education. Depending on the measurement issues discussed, we combine a variety of cross-sectional and longitudinal datasets, presented in Table 1.

For the cross-sectional analysis of students' occupational aspirations in grade 9, we rely on data from the PISA 2006 Supplementary Study for Germany, which drew on a representative sample of 39,216 school

[2] In the German education system, most students in grade 9 are 14 or 15 years old. The usual age for German students to graduate from upper secondary school—the prerequisite to enter higher education—is between 18 and 19. After that, they can go directly to a higher education institution to get a bachelor's degree in three or four years and then a master's degree in one or two years. Other, so-called traditional degrees, like State Examinations for medical doctors or lawyers, typically last six to seven years (see European Commission (2024)). Some of the male students in our sample were still obliged to complete military service for about one year between school and higher education. However, many other students also take time off during this period to do voluntary work or travel abroad (see Federal Statistical Office Germany (2018)).

Table 1 Description of used datasets

Dataset	**PISA-E 2006 supplementary study for Germany**	**Student statistic by the German Federal Statistical Office**	**German Microcensus**	**NEPS (National Educational Panel Study)**	
				Starting Cohort 4 (9th graders)	**Starting Cohort 5 (first-year students)**
Datatype	Cross-sectional survey data	Cross-sectional administrative data	Cross-sectional survey data	Longitudinal survey data	Longitudinal survey data
Year(s)	2006	2010 (first-year students) 2013 (Bachelor's graduation degrees) 2015 (Master's and traditional graduation degrees)	2014, 2015, 2016	2010–2017 (two waves/year)	2010–2019 (two waves/year)
Sample size	10,807	529,189 (2010); 430,688 (2013 + 2015)	2236	2860	5396
Concept(s)	Occupational aspirations age 15	Field of study choice at entry to higher education, graduation	Occupational choice after graduation	Occupational aspirations grades 9 and 12, field of study choice	Field of study choice, occupational choice
Classification(s)	ISCO-08	ISCED-97	ISCO-08	ISCED-97 + ISCO-08	ISCED-97 + ISCO-08
Problem(s) addressed	Definition of STEM, aspirations vs choices, cross-sectional vs longitudinal data	Aspirations vs choices, cross-sectional vs longitudinal data	Cross-sectional vs longitudinal data	Cross-sectional vs longitudinal data	Cross-sectional vs longitudinal data

students at about age 15 (Prenzel et al., 2010). Realistic aspirations were coded using the International Standard Classification of Occupations 1988 at the four-digit level (ISCO-88 4-digit). STEM coding is based on the translation of an ISCO-08 list of occupations by the tool iscogen (Jann, 2019) and subsequent manual recoding of individual occupations to ensure definition consistency between versions and datasets.[3] Since our STEM definition only includes occupations requiring higher education, we restrict our sample to students attending German school types that offer higher education entrance qualifications (*Gymnasium* and comprehensive schools). The final analysis sample consists of 10,807 school students in grade 9 (5916 girls and 4891 boys).

We use the student statistics provided by the German Federal Statistical Office (Federal Statistical Office of Germany, personal communication, May 11, 2020) to cross-sectionally analyze the subjects studied by German first-year college students in 2010 and their major subjects at graduation in 2013 for bachelor's degrees and in 2015 for master's and traditional[4] degrees. Majors are coded based on the International Standard Classification of Education 1997 (ISCED-97) at the three-digit level (United Nations Educational, Scientific & Cultural Organization, 2006). The final sample contains 529,189 first-year college students in 2010 (258,648 women and 270,541 men) and 430,688 college graduates, pooled for 2013 and 2015 (216,719 women and 213,969 men).

To cross-sectionally examine the first occupation held by the bachelor's graduates of 2013 and the master's and traditional graduates of 2015, we analyze the German Microcensus waves from 2014 to 2016.[5] The Microcensus is an official representative population survey conducted by the German Federal Statistical Office, which annually surveys a sample of 1% of the German population (Federal & State Statistical Offices Germany, 2021). Job entries for holders of bachelor's degrees are taken from the Microcensus surveys of 2014 and 2015, while information on job entries after a master's (or equivalent) degree is taken from the surveys of 2015 and 2016. The first job after graduation was measured as the job that began at least three months before graduation and lasted for at least six months, with a contractual work volume of 15 h per week or more. Graduates were included in the sample if employed according to this definition while pursuing their doctorate, which applies to about 80 percent of doctoral students in German academia (Wegner, 2020). Missing information on the field of research for

[3] The use of conversion keys leads to minor inconsistencies or occupations without a counterpart (here, 7 out of 586 occupations in the ISCO-08 system could not be assigned to any occupation in ISCO-88). In the subsequent manual review, we emphasized content coherence of the coded STEM subdomains. The latter also applies to the conversion and recoding between German KldB 2010 system (5-digit) and ISCO-08 (4-digit).

[4] Traditional degrees are equivalent to master's degrees and consist of State Examinations and *Diplom* or *Magister Artium*.

[5] Research Data Centre of the Federal Statistical Office and Statistical Offices of the Federal States, https://doi.org/10.21242/12211.2014.00.00.3.1.0 to https://doi.org/10.21242/12211.2016.00.00.1.1.0.

PhDs in the data is replaced by the field of study at graduation. Occupations are coded by ISCO-08 three-digit classifications.[6] The sample for job entries contains 2236 employed graduates, 1168 women and 1068 men.

Additionally, to assess the comparison between longitudinal and cross-sectional data, we used the German National Educational Panel Study (NEPS), starting cohorts (SC) 4 and 5 (Blossfeld & Roßbach, 2019).[7] Based on SC4, we followed a sample of students from grade 9 until they obtained a higher education entrance qualification and first enrolled in higher education by using up to four panel waves between 2010 and 2017. We balanced the panel on those students who enrolled in higher education, and accordingly excluded students who started an apprenticeship or left the school system without vocational training, along with those who dropped out of the panel. This resulted in an analytical sample of 2860 students (1546 women and 1314 men). We examined the development of their realistic occupational aspirations in grades 9, 11, and 12, which were coded using the ISCO-08 four-digit classification. Thereafter, we measured the first subject chosen in higher education using the ISCED-97 three-digit classification in order to assess the relationship between aspirations and choices.[8]

Based on SC5, we followed individuals from their first-time higher education enrollment in 2010 to their graduation and first labor market placement by using up to 15 waves until 2019. We balanced the panel on students who provided full information on the field of study at enrollment and at graduation and indicated their first employment in the spell data. In the process, we excluded students who dropped out of higher education and students who dropped out of the panel. The first job was defined in the same way as in the Microcensus. If individuals had parallel job episodes, we selected those episodes with longer duration, longer working hours, and/or higher skill level. This resulted in a second analytical sample of 5396 students (3410 women and 1986 men). We measured the leaky STEM pipeline with three (or four) measurement points: we analyzed students' majors using the ISCED-97 three-digit classification upon enrollment, after graduation from any degree program (when using three measurement points), or separately after graduation from a bachelor's or a master's program (for four measurement points). After graduation, we coded the first job based on the ISCO-08 four-digit classification. Since SC5 oversampled women, teacher training, and private higher education institutions, we applied sampling weights following the suggestions of Zinn et al. (2017).

We primarily measure the gender gap in absolute percentage point differences, as this has been the predominant approach in previous research (Alper, 1993; Ellis et al., 2016; Legewie & DiPrete, 2014; Morgan et al., 2013). Where there are significant deviations, we also report relative differences; however, it should be noted that these can become disproportionately large, particularly in cases of very small group sizes.

One additional important measurement issue relates to the question of how to handle missing values when assessing occupational aspirations. In the previous literature, the problem of missing values on students' occupational aspirations has either not been mentioned at all (Blanchard Kyte & Riegle-Crumb, 2017; Frome et al., 2006; Griffith, 2010) or has only been discussed in terms of its implications for data analysis. Previous studies use listwise deletion (Hägglund & Leuze, 2021; Wegemer & Eccles, 2019) or multiple imputation (Blaskó et al., 2018; Legewie & DiPrete, 2014) to deal with the problem of missing values. However, neither of these approaches seems adequate, given they both assume that values are missing completely at random. Yet, this may not be the case if we interpret these missing values as an indication of not having finished the process of occupational preference formation. Therefore, dropping these cases leads to an overestimation of the relative proportions of STEM aspirations and obscures any inflows from this category into the STEM pipeline in later stages of a longitudinal analysis. Moreover, students who do not report having any aspiration are selective with regard to both gender and socioeconomic characteristics (Staff et al., 2010). Therefore, it is important to treat the respondents who do not report having an occupational aspiration (yet) as a separate category and to analyze their behavior compared to other groups of students who have already reported having occupational aspirations.

[6] Although we consider a 4-digit measurement recommendable, the data protection regulation in the Scientific Use File of the German Microcensus does not provide information on the 4-digit codes which is why we use (exceptionally) a higher aggregation level for the cross-sectional measurement of the pipeline.

[7] This paper uses data from the National Educational Panel Study (NEPS): Starting Cohort Grade 9, https://doi.org/10.5157/NEPS:SC4:11.0.0 and from the Starting Cohort First-Year Students, https://doi.org/10.5157/NEPS:SC5:15.0.0. From 2008 to 2013, NEPS data were collected as part of the Framework Programme for the Promotion of Empirical Educational Research funded by the German Federal Ministry of Education and Research (BMBF). As of 2014, the NEPS survey has been carried out by the Leibniz Institute for Educational Trajectories (LIfBi) at the University of Bamberg in cooperation with a nationwide network.

[8] Coding for students' college major (field of study) varies between both cohorts. While in SC4, only the information on the first field of study is available, SC5 differentiates between major and minor fields of study. For both cohorts, we used the information on the first major. If more than one major was given, we gave preference to the STEM field; if several STEM majors were indicated, we randomly chose one.

Results

Defining the STEM pipeline in Germany

To illustrate the consequences of varying STEM definitions for measuring the leaky STEM pipeline, we applied different occupational classifications at various levels of aggregation and applied two official STEM definitions to the German case. We start with the occupational aspirations of grade 9 students based on the PISA 2006 complementary study for Germany. To measure STEM occupations, we apply the official definition of STEM occupations provided by the German Federal Employment Agency (FEA) (2017),[9] but restrict our analyses to STEM fields requiring higher education (FEA Germany, STEM Core). By using the official STEM definition of the German FEA, we could account for the specificities of the German labor market. At the same time, by converting national classifications into international coding schemes, we allow for better comparability of our results across countries. We further subdivide the STEM Core category into science and mathematics (MaSc) on the one hand and engineering and technology (Tech) on the other to account for the heterogeneous gender distribution within the STEM field (see Mann and DiPrete, (2013), for a similar differentiation). To perform robustness checks with a broader STEM definition, we additionally compare the gender distribution in the STEM Core definition with the one provided by the International Labour Organization, which additionally includes healthcare occupations in the STEM category (ILO STEM + Health).[10]

Figure 1 presents the weighted distributions of realistic occupational aspirations among German 9th graders, separately for girls and boys. When applying the official STEM definition of the German FEA (FEA Germany, STEM Core), we immediately see that gender differences in STEM aspirations already exist among adolescents at age 15. Even though both male and female adolescents predominantly aspire to a non-STEM occupation, the share of boys who aspire to a STEM occupation is about 11 percentage points larger than that of girls (32.1% vs. 21.5%). According to this definition, the relative share of girls aspiring to STEM occupations in grade 9 is about 50% lower than the share of boys.

The further differentiation of STEM Core into mathematics and sciences on the one hand and technology and engineering on the other hand reveals important within-STEM variations. While in absolute percentage points gender differences are less pronounced in the mathematics and science subfield (5.0% girls, 8.4% boys), they are much larger in the engineering and technology subfield (16.5% girls, 23.6% boys). For relative differences a different picture emerges: the share of boys aspiring to a mathematics and science occupation is about two-thirds higher, while the share of boys aspiring to a technology and engineering occupation is 43% higher than the share of girls. From this perspective, gender differences are more pronounced in mathematics and science than in technology and engineering. However, these latter findings are mainly the result of a rather low number of both, young men and young women aspiring to mathematics and science in grade 9. When we broaden the STEM definition by including healthcare occupations (ILO STEM + Health), the distribution becomes more balanced for both genders (39.1% girls, 50.8% boys, about 30% more boys than girls aspire STEM). This supports findings for the US, according to which a broader definition of STEM leads to lower gender gaps in students graduating from STEM fields (Baum et al., 2015). As a robustness check, we also calculated the distribution of men and women in the aforementioned fields for entry

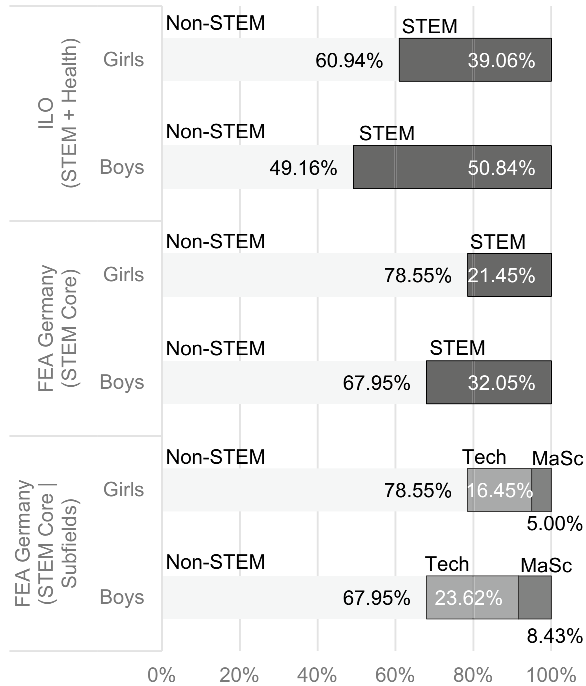

Fig. 1 Gender differences in STEM aspirations among grade 9 students in Germany. *Note:* Occupational aspirations of grade 9 students, sample of school students from Gymnasium and comprehensive schools. Acronyms: 'Tech' refers to occupational fields in engineering and technology; 'MaSc' refers to occupational fields in mathematics and science. Source: PISA-E 2006 ($N = 10{,}807$); authors' calculations, weighted. Pearson's χ^2 tests show that all differences between girls and boy's aspirations are highly significant (degrees of freedom in parentheses; $X^2_{ILO}(1) = 149.71$, $p = 0.00$; $X^2_{FEA\ Core}(1) = 154.91$, $p = 0.00$; $X^2_{FEA\ Subfields}(2) = 158.24$, $p = 0.00$)

[9] The initial information was generated from the German KldB and converted to ISCO-08, respectively, ISCO-88.

[10] All coding is available by request from the authors.

into higher education and reached the same conclusion (see Appendix A in Additional file 1).

Our results show how various definitions of STEM subjects and occupations can substantially influence results regarding the leaky STEM pipeline. By applying the rather restrictive German definition of STEM, we obtain lower STEM shares for both genders, but also more gender differences than with the broader International Labour Organization (ILO) definition. By further differentiating the subfields of mathematics and science versus engineering and technology, we replicate earlier findings that gender differences are predominantly present in the technological field, while the natural science field is more balanced, at least when measured in absolute terms (Mann & DiPrete, 2013; Schoon, 2001).

STEM occupational aspirations versus subject choices in Germany

In the following, we investigate whether gender differences in realistic STEM aspirations differ from gender differences in actual STEM major choices in Germany. To do so, we compare girls' and boys' realistic occupational aspirations indicated at age 15 with their chosen major at the time of higher education enrollment (see Fig. 2). To ensure international comparability, majors held at higher education entry are recoded from the original German classification of the Federal Statistical Office into the field of study codes as provided by the International Standard Classification of Education 1997 (ISCED-97) (United Nations Educational, Scientific & Cultural Organization, 2006). Similar to Fig. 1, we do not focus on the STEM category as a whole but differentiate between mathematics and science on the one hand and engineering and technology on the other. However, for occupational aspirations, we also include those grade 9 students who have not yet made up their minds about which occupations they aspire to.

The first issue that becomes obvious when looking at Fig. 2 (middle panel) is the large share of 15-year-old boys (35%) and girls (28%) in secondary education who do not provide an explicit occupational expectation. The category includes both missing values, vague answers, and explicit "don't know" statements. It seems that, at least in Germany, about one-third of boys and girls at age 15 have not yet finished this process of occupational preference formation and are, therefore, unable (or unwilling) to state an explicit occupational aspiration. Such an interpretation implies that girls and boys with unknown occupational aspirations should be explicitly included in the analysis to understand the role this subgroup of "late decision makers" plays in the leaky STEM pipeline.

A closer look at the actual major choices among higher education entrants (lower panel) indicates that gender

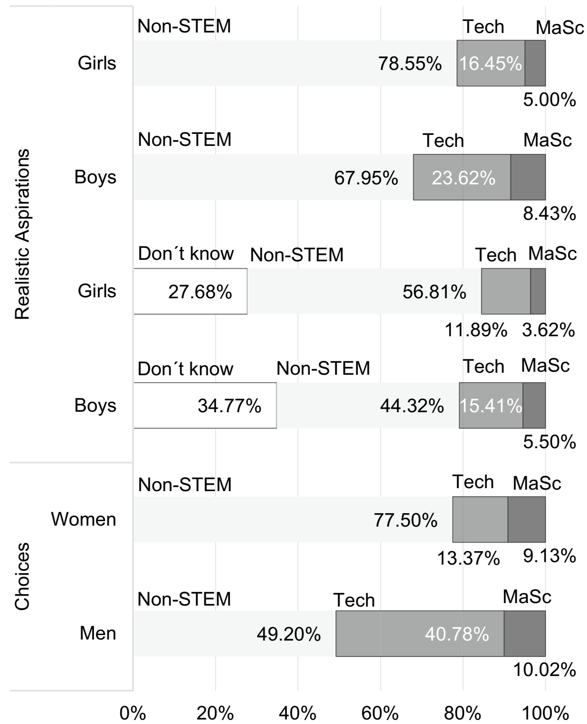

Fig. 2 Occupational aspirations and major choices in STEM. *Note:* Occupational aspirations of grade 9 students, sample of school students from Gymnasium and comprehensive schools. Choices (of field of study) from first-year students of German higher education institutions. Acronyms: 'Tech' refers to occupational fields and fields of study in engineering and technology; 'MaSc' refers to occupational fields and fields of study in mathematics and science. Sources*:* PISA-E 2006, $N = 10{,}807$, weighted, Destatis students' statistics 2010/13/15, $N = 529{,}189$; authors' calculations. Pearson's chi2 tests show that all differences between girls and boy's aspirations are highly significant (degrees of freedom in parentheses; $X^2_{PISA}(3) = 253.68$, $p = 0.00$; $X^2_{Destatis}(2) = 53{,}000$, $p = 0.00$)

differences in mathematics and science are even smaller than for occupational aspirations (9.1% women, 10.0% men). In contrast, even more pronounced gender differences occur regarding the choice of engineering and technology majors (13.4% women, 40.8% men), which is 200% more men than women choosing a major in engineering and technology against 10% in mathematics and science. These numbers again support our decision to further differentiate the STEM category. Moreover, when comparing actual choice to aspirations (including students with unknown preferences), our empirical evidence suggests that young men who previously had no clear occupational aspiration opt in larger numbers for science, technology, engineering and mathematics subjects when making a choice, while the share of men who chose non-STEM subjects is comparable to the share of male school students preferring non-STEM occupations. In contrast, young women with unclear occupational preferences more strongly opt for non-STEM subjects, even though the share of women in mathematics and science and engineering and technology subjects likewise increases.

Overall, to understand the leaky STEM pipeline, including both aspirations and choices, allows to cover a longer period of the life course and allow for an "inflow" of students who opt for a STEM career when entering higher education without having reported a STEM aspiration in school. Comparing STEM occupational aspirations in secondary education with STEM subject choices in higher education in Germany, we do not find a clear indication of a leakage, even in the case of young women. However, since these findings are based on comparing two cross-sectional datasets, they cannot show the actual processes at the individual level, which only becomes apparent when using longitudinal data.

Cross-sectional and longitudinal results on the leaky STEM pipeline in Germany

To compare cross-sectional with longitudinal findings on the leaky STEM pipeline in Germany, we first expand the number of cross-sectional measurement points by combining data from PISA 2006, the Federal Statistical Office of Germany, and the German Microcensus. Thus, we can measure the STEM pipeline from occupational aspirations at age 15, through the choice of major at entry and graduation in higher education, up to the occupation held at job entry. Figure 3 shows the share of male and female individuals in our three subfields.

Overall, women are consistently underrepresented in the engineering and technology fields and overrepresented in non-STEM fields at all points of observation. In contrast, mathematics and science fields are largely gender-integrated. At the same time, we do not find clear leakage patterns. The gender gap in the engineering and technology fields increases the most from aspirations at age 15 from one-third (24% men vs. 16% women) to 70% when choosing a major at entry to higher education (41% men vs. 13% women). However, this change is due mainly to young men moving into engineering and technology subjects rather than young women leaving these fields. After that, the share of women in engineering and technology remains fairly stable, while the gender gap even decreases upon labor market entry due to a leakage of men. In the mathematics and science fields, the gender gap is small from the beginning and almost non-existent in higher education and upon labor market entry. The only leakage occurs for both genders at job entry (men: 9–4%, women: 9–3%). Thus, pooled cross-sectional data for Germany indicate that women only leak out of the STEM pipeline in the engineering and technology fields

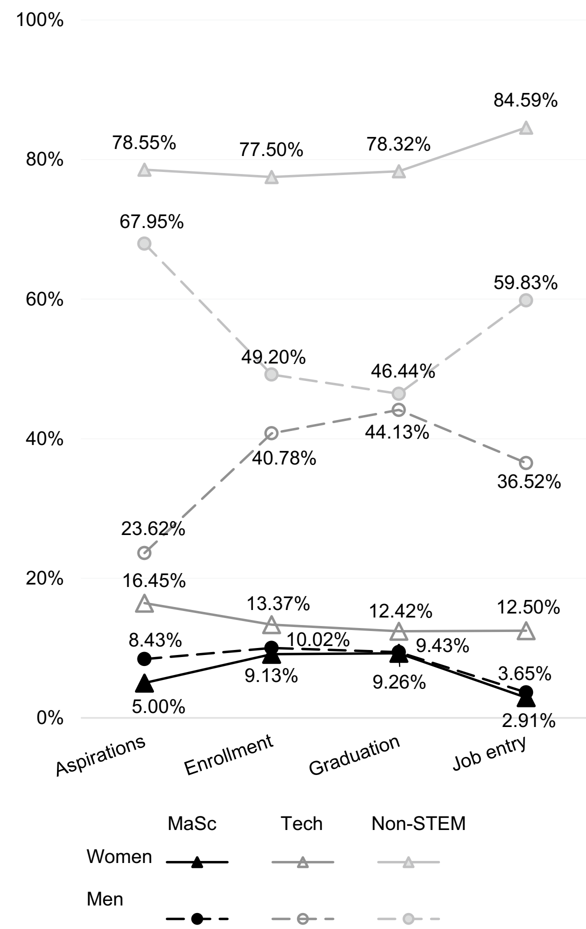

Fig. 3 Measuring the STEM pipeline with cross-sectional data. *Note:* Occupational aspirations of grade 9 students, sample of school students from Gymnasium and comprehensive schools. Choices (of field of study) from first-year students of German higher education institutions to their last graduation degree. Occupational choice of labor market entrants. Acronyms: 'Tech' refers to occupational fields and fields of study in engineering and technology; 'MaSc' refers to occupational fields and fields of study in mathematics and science. Sources: PISA-E 2006, $N=10{,}807$, weighted; Destatis student statistics 2010/13/15 ($N=529{,}189/N=430{,}688$) and Microcensus 2014/15/16 ($N=2236$); authors' calculations. Pearson's χ^2 tests show that all differences between girls and boy's aspirations are highly significant (degrees of freedom in parentheses; $X^2_{Aspirations}(2)=158.24$, $p=0.00$; $X^2_{Enrollment}(2)=53{,}000$, $p=0.00$; $X^2_{Graduation}(2)=56{,}000$, $p=0.00$; $X^2_{Job\ Entry}(2)=67.65$, $p=0.00$)

when comparing their aspirations in school with their college major choices.

This picture changes only slightly when we use longitudinal data with two measurement points for aspirations (grades 9 and 12) and compare them to higher education enrollment, graduation, and job entry. The analyses of the first three measures are based on NEPS SC4, while the latter three are based on NEPS SC5. When looking at aspirations, we also consider students who did not indicate a clear occupational aspiration. Since we balanced SC4 for those school students enrolling in higher education, who might be a highly selective group, we measure major choice in higher education enrollment twice to compare the distribution of SC4 with the representative first measure of SC5.

Figures 4 and 5 present Sankey diagrams, which represent the proportions of occupational and study fields by quantity-proportional arrows across different measurement time points for men and women, respectively. For example, in Fig. 4, 5% of the female students have career aspirations in Tech in 9th grade. About half of them change their occupational aspirations to a non-STEM occupation in 12th grade, with only a minority keeping their Tech aspirations. At the same time, the proportion of women interested in Tech in 12th grade increases by 2 percentage points to 7%, due an influx of female students who were interested in non-STEM occupations or who had no specific occupational aspirations ("don't know") in grade 9.

Comparing the shares from Figs. 2 and 3 with those in Figs. 4 and 5, we note that the longitudinal results differ only slightly from the cross-sectional numbers. The proportions of women and men in mathematics and science and engineering and technology are slightly lower for occupational aspirations, due to the larger share of "don't knows", but are somewhat larger in higher education, particularly in mathematics and science. The trend across observation points is rather similar, which indicates the high quality of our longitudinal data and suggests that selectivity problems arising from the balanced panel can be considered marginal. This is also supported by a comparison of the enrollment rates at higher education entry in SC4 and SC5.

However, the longitudinal perspective reveals strong volatility from one measurement point to the next, which cross-sectional data cannot capture. Moreover, this volatility increases when additional measurement points are considered, as shown by graphs in Appendix B and Appendix C in Additional file 1. Especially in school, occupational aspirations are less constant over time, as suggested by the cross-sectional literature. During school, the overall persistence of STEM aspirations is rather low for both genders. This changes once young

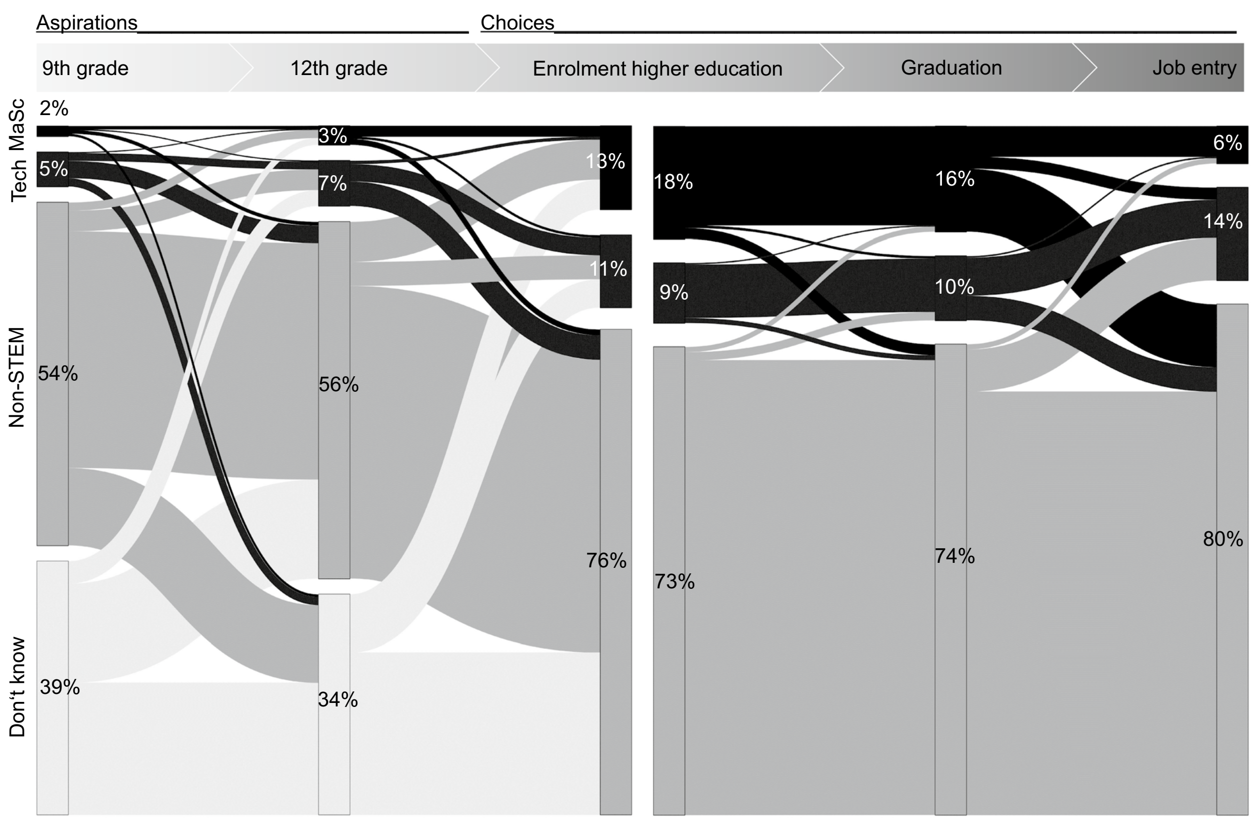

Fig. 4 Longitudinal STEM pipeline for women. *Note:* 'Tech' refers to occupational fields and fields of study in engineering and technology; 'MaSc' refers to occupational fields and fields of study in mathematics and science. Source: NEPS Starting cohort 4 (wave 1–11; $N=1546$) and 5 (wave 1–15; $N=3410$). Authors' calculations

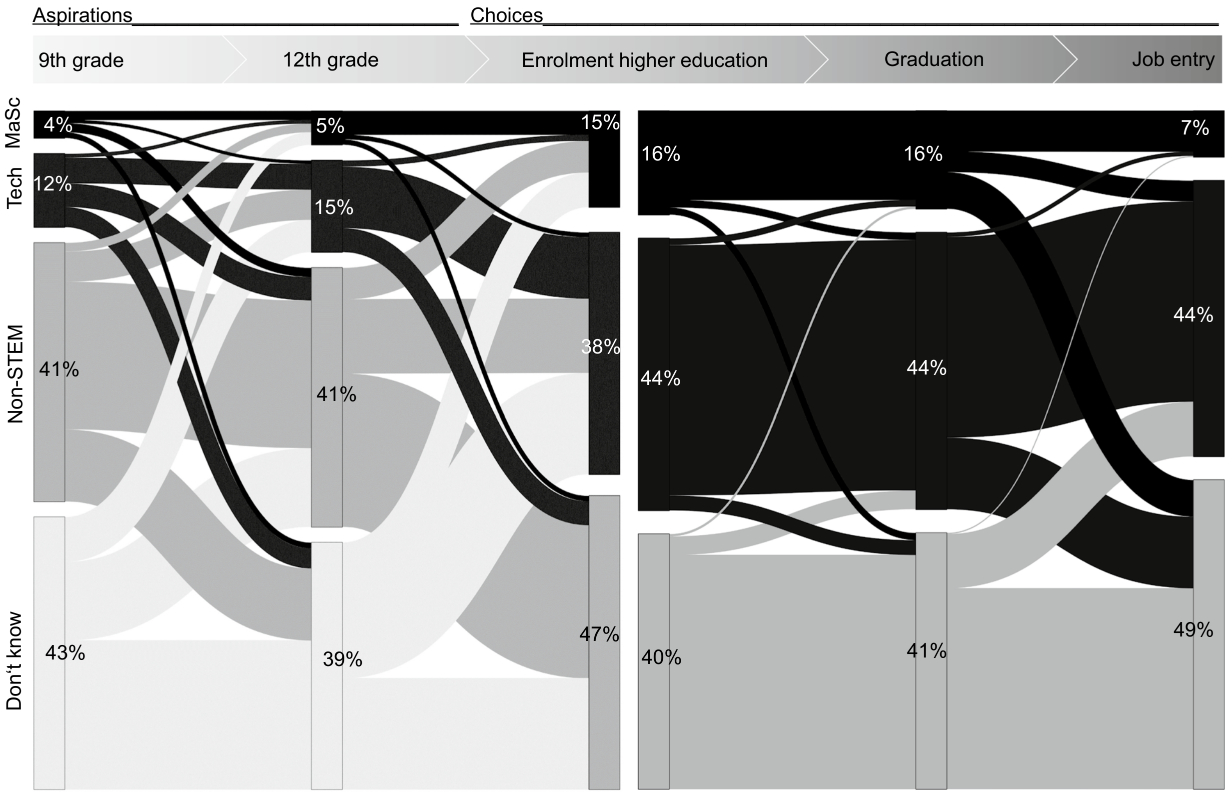

Fig. 5 Longitudinal STEM pipeline for men. *Note:* 'Tech' refers to occupational fields and fields of study in engineering and technology; 'MaSc' refers to occupational fields and fields of study in mathematics and science. Source: NEPS Starting cohort 4 (wave 1–11; *N* = 1314) and 5 (wave 1–15; *N* = 1986). Authors' calculations

men and women opt for a STEM field in higher education. However, rather than a leakage, we observe an increase in both engineering and technology and mathematics and science fields for young men and women. The inflow from school students without clear occupational aspirations ("don't know") seems to be important for young women and men who opt for a STEM major, since about a third of STEM enrollments come from this category. Once this initial choice at higher education entry has been made, we observe high stability in STEM trajectories until graduation, at least within our broad categories. The only point of leakage is at labor market entry, with an especially high leakage of women and men from math and science fields into the non-STEM category. However, we also find STEM inflows, since the share of women in the engineering and technology fields even increases at the transition to the first job.

Overall, the longitudinal view reveals much higher volatility in the educational trajectories of young women and men between different STEM and non-STEM fields than seen with cross-sectional data, particularly regarding occupational aspirations. However, due to selectivity problems in these data sets, a robustness check with cross-sectional data is recommended—which, in our case, shows similar shares and developments to an analysis based on longitudinal data.

Discussion

The underrepresentation of women in STEM majors and occupations is a long-standing issue in educational sociology. Previous studies showed that girls and young women are underrepresented in STEM at all stages of the educational trajectory. Numerous studies have used the metaphor of a "leaky pipeline", examining the circumstances under which women persist (or do not persist) in STEM fields, to describe the development of the share of women in STEM careers over the life course. However, the pipeline metaphor is increasingly being criticized. In this paper, we add to the critical literature by discussing challenges that arise from design variations and their impact on the measurement of the STEM pipeline. Based on a review of the previous literature, we have shown that the phenomenon is largely dependent on three research design aspects that are reflected in our research questions: (1) the exact definition of which subjects and occupations are considered as STEM, and how they are measured (RQ1); (2) whether the analysis includes only STEM-related choices, only aspirations, or a combination of both (RQ2); and (3) whether studies are based on pooled cross-sectional or longitudinal data (RQ3).

From our literature review, we derive the following suggestions for how to measure the STEM pipeline in a comparable manner, both across studies, time and country context:

(1) It is essential to have a precise STEM definition that is not based on the judgement of individual researchers but which relates to official bodies, either national or international. Although in single-country studies, national definitions have advantages as they better reflect the national context, they should be coded by means of international classifications of occupations or majors to ensure international comparability. A stricter definition of STEM is advisable, as including more gender-balanced fields like social sciences or healthcare decreases the gender segregation associated with STEM. It is advisable to further differentiate within the broad STEM category to compare the more gender-integrated fields of mathematics and natural sciences with the highly male-dominated technical and engineering fields.

(2) To measure the STEM pipeline, starting from an early age, we suggest combining measures of occupational aspirations and educational choices. Only such a research design allows us to understand the association between earlier occupational preference formation in school and later choices in higher education or on the labor market. Moreover, the inclusion of aspirations and choices allows us to capture the "inflow" of students who opt for a STEM career, but who are unable (or unwilling) to state an explicit occupational aspiration at the age of 15. Finally, cross-national differences of the leaky STEM pipeline might stem from varying relations between STEM aspirations and choices, which might be more closely connected in countries with strong occupational boundaries, such as Germany.

(3) We have shown that a "pipeline" can only be analyzed properly using longitudinal data, preferably over a long period of time. Only by following individuals over their educational and occupational careers can it be established at which points (young) men and women enter the STEM pipeline, how long they persist, and at which points exit, i.e., leakages, occur. To address problems related to longitudinal data, especially panel attrition and subsequent low case numbers, we suggest using cross-sectional data to check the validity of distributions at specific points of the life course. Moreover, longer observation periods and more points of observations should be preferred over the analysis of single transitions, since they allow researchers to identify the exact point in time when (young) women decide for or against a STEM career.

We have demonstrated the empirical consequences of these research design variations by tracing the leaky STEM pipeline for the case study of Germany. Generally, our assessment of the STEM pipeline in Germany indicates that (young) women already show lower aspirations for STEM in secondary school, particularly regarding technical and engineering occupations. The underrepresentation of women in engineering and technology increases slightly when choosing majors in higher education, and remains stable after graduating and starting the first job. We found hardly any gender differences in the fields of mathematics and science, again from aspirations to major choices to first occupations held. This supports our suggestion to opt for a narrow definition of STEM and to further differentiate between more and less gender-balanced domains (Mann & DiPrete, 2013; Schoon, 2001; Sikora, 2019). Overall, we conclude that decisions on the research design in its different dimensions impact the measurement of the STEM pipeline and, in turn, influence the substantial results.

However, in contrast to findings for the US (Ellis et al., 2016; Legewie & DiPrete, 2014), Australia (Sikora, 2019) or the UK (Schoon, 2001), we do not find a "leaky STEM pipeline" in Germany. Rather, the share of (young) women (and men) in both STEM categories—mathematics/science and engineering/technology—increases once actual decisions must be made upon entering higher education when compared to students' occupational aspirations at age 15. The larger gender gap in STEM fields in higher education exists because more young men decide for STEM, not because of women dropping out of the pipeline. After entering higher education, the share of women (and men) in STEM remains rather stable. Women (but also men) leave the STEM pipeline only when they enter the labor market for the first time, especially after graduating with a degree in mathematics or natural sciences. At the same time, the share of women working in engineering and technology even increases compared to the share of women among the graduates in this field. Empirically, this picture could only emerge by combining data on aspirations with data on actual choices, and by including young adults with uncertain occupational preferences in our sample. Moreover, assessing the pipeline based on cross-sectional and longitudinal data validated the robustness of our findings. Overall, considering aspirations and decisions when measuring the STEM pipeline by means of longitudinal data allowed us to assess the exact leakage points in the educational career.

Germany has served as an empirical example characterized by a strong school-to-work linkage, a high degree of occupational specificity, and strong school tracking (Allmendinger, 1989; Kerckhoff, 1995). Paths taken have long-lasting consequences for occupational placement and mobility (Gangl, 2001). This institutional background might explain why gender differences in STEM aspirations (especially regarding engineering and technology) are already prevalent in secondary school, but also why the observed leakage in higher education and upon labor market entry is much lower than in Anglo-Saxon systems, which are characterized by less tracking and lower occupational specificity. Thus, for Germany, we see three main areas for future research: first, the need to better understand early gender differences in occupational aspirations and the volatile processes of aspirations during school; second, the need to focus more strongly on school students who have not yet made up their minds about which occupations to strive for; and third, the need to investigate the processes at labor market entry where young women who have continued in the pipeline until graduation are most at risk of leaking out, at least from the field of mathematics and science.

Moreover, systematic cross-national comparisons can shed light on whether the stratification and occupational specificity of educational systems not only affects school-to-work linkages in general (Gangl, 2001), but also the gendered nature of the leaky STEM pipeline. In addition, our analyses on Germany reflect the political, social, and economic situation of the time when the data were collected, since participants' responses are affected by the historical and cultural context in which they are assessed. However, societal attitudes and beliefs associated with gender stereotypes and STEM are likely to change as women become more noticeable in STEM fields. Also, historical events such as the COVID-19 pandemic and emerging societal issues, such as climate change, affect students' awareness of science and technology. For example, it has been shown that STEM occupations are less sensitive to recessions, like the Great Recession and COVID-19 pandemic, than non-STEM occupations (Davis et al., 2021). Thus recessions might push both women and men towards STEM majors (Liu et al., 2019). Future research should take these historical changes into account and compare students from different cohorts to assess how such changes might impact their career interests in STEM.

Conclusion

The metaphor of the "leaky STEM pipeline" has recently been criticized, both in terms of its linguistic meaning (Tajmel, 2019) and its empirical appropriateness (Cannady et al., 2014; Miller & Wai, 2015; Nitzan-Tamar & Kohen, 2022). Xie and Shauman (2003) already argued two decades ago that the pipeline metaphor suggests a normative and oversimplified educational pathway, alternatively proposing a life-course conceptualization for understanding STEM careers. In addition to these conceptual considerations, our discussion of challenges when measuring STEM careers over the life-course questions whether the metaphor of a leaky pipeline adequately empirically captures the trajectories of men and women in STEM, at least in a central European country like Germany. Therefore, we support those who are skeptical about the appropriateness of the pipeline metaphor (Cannady et al., 2014; Nitzan-Tamar & Kohen, 2022; Sevilla et al., 2023; Xie & Shauman, 2003). Instead, we find it more useful to employ a terminology used in life-course research that considers the trajectories of women and men in the field of STEM as a series of transitions (Elder, 1998). At each of these transitions, women and men can enter and exit the field of STEM, allowing researchers to empirically capture all kinds of STEM trajectories. Such an alternative theoretical framing should go hand in hand with measurement standards that include a STEM definition which relies on official bodies; a long observation period that ideally combines the analysis of aspirations with actual choices from school to labor market entry; and an analysis based on longitudinal data that allows researchers to observe the STEM trajectories of individuals over the longer periods of their lives.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40594-024-00512-4.

Additional file 1.

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Author contributions

Antje Stefani analyzed and interpreted the Microcensus data, Student Data of the Federal Statistical Office and National Educational Panel Study Starting Cohort 5. Ralf Minor analyzed and interpreted the PISA-E-2006 data and National Educational Panel Study Starting Cohort 4. All authors were major contributors in writing the manuscript.

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Availability of data and materials

The data that support the findings of this study are available from IQB—Institute for Educational Quality Improvement, Federal Statistical Office Germany and Leibniz Institute for Educational Trajectories (LIfBi) but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available.

Declarations

Competing interests
The authors declare that they have no competing interests.

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