Source and Accuracy of the 2020 Post-Enumeration Survey Person Estimates

2020 Post-Enumeration Survey Methodology Report

Elizabeth Marra and Timothy Kennel

Issued March 2022

PES20-J-01

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Patrick J. Cantwell
Division Chief, Decennial Statistical Studies Division

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MEMORANDUM FOR	Patrick J. Cantwell Chief, Decennial Statistical Studies Division
From:	Timothy L. Kennel Assistant Division Chief, Statistical Methods Decennial Statistical Studies Division
Prepared by:	Elizabeth Marra and Timothy L. Kennel Decennial Statistical Studies Division
Subject:	Source and Accuracy Statement of 2020 Post-Enumeration Survey Person Estimates

This memorandum documents the Source and Accuracy Statement of person estimates for the 2020 Post-Enumeration Survey. Please direct any inquiries to Elizabeth Marra at (301) 763-7760 or Timothy L. Kennel at (301) 763-6795.

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1. INTRODUCTION

This document describes the source of the data collected and the accuracy of the person estimates produced by the 2020 Post-Enumeration Survey (PES).[1] Another source and accuracy statement covers PES housing unit estimates. The 2020 PES was an independent evaluation of the 2020 Census. Its primary objective was to estimate the amount of net coverage error and the components of coverage of the 2020 Census.

Net coverage error refers to the difference between the census count and the true population size. To estimate the true population size, the 2020 PES used a technique called "dual-system estimation," with the two systems being the survey and the census. With this technique, the survey independently interviewed people, asked where they lived on April 1, 2020 (the reference day for the census), and then matched that information to the census results. The survey took more than 2 years and involved enumerating housing units and people in about 10,000 blocks across the country.

After we matched these people to the list of people in the census, we were able to determine who was counted:

- In the census only.
- In the PES only.
- In both the census and the PES.

We used this information to estimate how many people were in the United States and how many people were correctly counted in the census.

In fact, we used data from both the PES and the census in the estimation process. One of the advantageous aspects of dual-system estimation is that two imperfect sources are combined to estimate the population size more accurately than either could on their own.

Through PES fieldwork, follow-up, and analysis, we also estimated the proportions of census records that were correct, wrong, or lacking enough information to confirm whether they were correct or wrong. The PES report included these "components of coverage," which broke final census counts into the following three groups:

- **Correct enumerations**. These referred to people counted in the census who were living in the United States on April 1, 2020. According to the PES, the individuals should have been and were counted in the census.
- **Erroneous enumerations**. According to the PES, these included duplicate records of people who were already counted in the census, as well as people who were counted but should not have been. For example, they may have died before April 1, 2020, or were just visiting the country.
- **Whole-person census imputations**. For some records in the census, the enumeration did not include enough characteristics, so the U.S. Census Bureau used a statistical technique called whole-person imputation to create a valid person record.

To determine the size of the three categories, we counted how many census records needed whole-person imputation and used the PES follow-up to estimate the correct and erroneous enumerations.

[1] The Census Bureau's Disclosure Review Board has reviewed this product for unauthorized disclosure of confidential information and has approved the disclosure avoidance practices applied to this release. CBDRB-FY22-137.

2. SOURCE OF THE POST-ENUMERATION SURVEY (PES) ESTIMATES

In this section we introduce the target population of the PES. We also provide a description of the Population (P) and Enumeration (E) samples.

Target Population

The target population for the 2020 PES was slightly different from that of the 2020 Census. While both programs aimed to count all people in the United States and Puerto Rico as of Census Day (April 1, 2020), the PES excluded people living in Remote Alaska areas[2] or in group quarters. Remote Alaska areas were out of scope because the PES could not accurately conduct the matching and follow-up operations necessary for dual-system estimation. This was due to the seasonal nature of the addresses and population in these areas. For example, people living in Remote Alaska areas during the census might not be living there during the PES interviews. People living in group quarters were out of scope because the populations often change between census enumerations and PES enumeration operations. Group quarters include jails, nursing homes, college dormitories, homeless shelters, and military personnel living in barracks or on ships (U.S. Census Bureau, 2020).

The Population-Sample People

The P sample was made up of independent enumerations in sample areas across the country. It provided information about people who were missed in the census. To create the P sample, we began with a probability sample of blocks.[3] Using a stratified, three-stage, systematic sample design, we aimed to achieve a target housing unit sample size of 171,000 housing units across the 50 states and the District of Columbia, and 9,000 housing units in Puerto Rico. In the first stage, we selected an initial sample of blocks. Within these blocks, the PES conducted a listing of the housing unit addresses without referring to any address lists used in the census enumeration. In the second phase, we removed a subsample of small blocks based on additional information collected during the independent listing. Small blocks were defined as having zero, one, or two housing units. Traveling to small blocks could be an inefficient use of time and resources, so they were subsampled to reduce travel costs and save time. In the third sampling phase, we subsampled segments of housing units from large blocks. Our final sample size was roughly 160,000 housing units across the 50 states and the District of Columbia, and roughly 7,000 housing units in Puerto Rico (Hill, 2022).

Once sampling for the P sample was completed, we started the Person Interview field data collection. The date of the PES person interview was referred to as "Interview Day" and could have occurred any time during the Person Interview field data collection operation. In this operation, in-person interviews were attempted at each sample housing unit. We rostered each person in the P-sample household on Interview Day and asked where they were living on Census Day. The interview also asked respondents about who was living at the housing unit on Census Day.

Since the PES Interview Day took place months after Census Day, we had to account for changes to the population that occurred between these two dates. For example, babies born after April 1, 2020, were not part of the target population. However, this may have caused confusion for the respondent if their baby was born between Census Day and Interview Day. During the Person Interview operation, it could have been unclear to them as to whether they should include their child. Our goal was to include the people who were part of the target population described above. That is, we wanted to include the household population outside of Remote Alaska areas on April 1, 2020. Nevertheless, the issues like the one described above and the time between Census Day and Interview Day made it harder for the PES to do this.

One important issue that the PES dealt with was the treatment of movers. Between Census Day and Interview Day, people moved into and out of housing units in the PES sample blocks. We rostered every person living at the P-sample housing unit on Interview Day. Using the answers to the Interview Day questions, we made determinations as to whether these people were inmovers or nonmovers. Between Census Day and Interview Day, those who moved into

[2] Remote Alaska refers to the Remote Alaska enumeration area as defined by the 2020 Census. A map of the Remote Alaska enumeration area is available in the "2020 Census: Type of Enumeration Area (TEA) Viewer" located at <www.census.gov/newsroom/press-releases/2019/tea-viewer.html>.

[3] Technically, the PES sampled Basic Collection Units or BCUs, which roughly corresponded to a block.

a P-sample housing unit were referred to as “inmovers.” People who did not move at all were referred to as “nonmovers.” The third class of people, called “outmovers,” moved out of a P-sample housing unit between Census Day and Interview Day. Generally, whole households of outmovers could only be captured through proxy interviews, because they were not available for interviews at the P-sample housing units.

We used Procedure B (United Nations Secretariat, 2010) to determine how movers should be handled in the P sample. Procedure B says that the P sample should include inmovers and nonmovers but exclude outmovers. Although outmovers were not included in the P sample, information about them was collected during the Person Interview operation for use in the E sample. Procedure B relies on a balance in the population between inmovers and outmovers. That is, every inmover to a P-sample housing unit was typically an outmover from another block, and every outmover from a P-sample housing unit was also an inmover to another block. There were exceptions, for example, when one considers movement between housing units and group quarters.

Once the Person Interview operation finished, we reviewed the P-sample rosters, removing any duplicates and erroneously included people. Examples of erroneous inclusions were people who were in scope, but were rostered at the wrong address, duplicates of people, or even fictitious people. An example of an out-of-scope person would be a baby born after Census Day or a person who lived outside the country on Census Day. Then, the people rostered during the Person Interview operation were matched to the census.

The final P sample was a dataset of in-scope real people and housing units. For each person in the P sample, computer and clerical matching operations determined whether the person was found in the census or not, which we referred to as their match status. If we were unable to determine match status, we imputed a match probability.

The Enumeration-Sample People

The E sample provided information about correct and erroneous enumerations in the census. For dual-system estimation, the main function of the E sample was to identify people who were correctly enumerated in the census. To be correctly enumerated, a person must have been enumerated at the location where they were living most of the time on April 1, 2020. Hogan (2003) proposed four dimensions that define the concept of correct enumeration:

- Appropriateness: A person should be included in the census. For example, it is not appropriate to include a tourist or family pet in the census. We also exclude people who are born after Census Day or who die before Census Day.
- Uniqueness: This refers to the concept of “counted once and only once.” It is possible for a person to be counted in the census two or more times. For purposes of the dual-system estimation, we removed these duplicates.
- Completeness: The enumeration must have enough identifying characteristics to identify a real person and confirm whether the person was also counted in the P sample.
- Geographic correctness: A person’s geographic location in the census is where they reside. There are two dimensions that define geographic correctness:
    - Correct location.
    - Area of search around the correct location.

The E sample contained census enumerations in the same sample blocks as the P sample. While it was not necessary to overlap the E and P samples in this manner, it was a feature of our sampling framework for the 2020 PES. It improved cost-effectiveness by consolidating the P-sample and E-sample follow-up interviews in the same areas. Once data collection in the census was completed, we determined whether each census enumeration in the E sample met the four dimensions for correct enumeration. We began by attaching any matching information from the P sample to the E sample. From there, we determined whether each enumeration was correct or erroneous, or needed field follow-up. Finally, each follow-up case was interviewed to determine enumeration status. The final E-sample sizes were roughly 180,000 housing units across the 50 states and the District of Columbia, and roughly 7,500 housing units for Puerto Rico (Phan, 2022).

3. POST-ENUMERATION SURVEY (PES) COVERAGE ESTIMATION

In this section we discuss dual-system estimation and components of coverage.

Dual-System Estimation for People

The PES estimated the size of the true population using dual-system estimation at national and state geographies and for various estimation domains like race and sex. People in the E sample made up one system, while people in the P sample made up the second system. As previously described, the E sample was a sample of the census housing units and person enumerations; the P sample was derived from a PES listing of housing units, independent of the census, in the same sample geographies as the E sample. Everyone in the target population was either:

- Correctly enumerated in only the census.
- Correctly enumerated in only the PES.
- Correctly enumerated in both the census and the PES.
- Enumerated in neither the census nor the PES.

These groups are shown in Table 1.

In theory, all cells are observable, except those highlighted in gray (N_{22}, N_{2+}, N_{+2}, and N_{++}). Note that N_{++} represents the true population total. Under the assumption of statistical independence between the PES and the census, we can estimate the total population, N_{++}, in the following way:

$$\widehat{N}_{++} \approx N_{+1}\left(\frac{N_{1+}}{N_{11}}\right)$$

This is the classic formation of the dual-system estimate (DSE) (Wolter, 1986), also known as the Petersen (1896) or Sekar-Deming (1949) estimator. Note that (N_{1+}/N_{11}) is the inverse of the match rate for the PES, and N_{+1} is the number of correctly enumerated people in the census. In 2010 and 2020, the post-enumeration surveys applied a dual-system estimator that was motivated by the Petersen or Sekar-Deming estimator, but was more flexible and robust, namely a synthetic DSE (Wolter, 1986). We used logistic regression models developed on the P and E samples to predict the probability of being a match and correct enumeration, respectively. Additionally, we modeled the probability that a census enumeration was data-defined (i.e., not a whole-person imputation). Finally, to each census enumeration—based on its characteristics—we applied these modeled probabilities as in the following equation to calculate a Coverage Correction Factor (CCF):

$$CCF_j = \pi_{dd,j}\frac{\pi_{ce,j}}{\pi_{m,j}}$$

where

- j is the census enumeration.
- $\pi_{dd,j}$ is the predicted probability that the census enumeration is data-defined.
- $\pi_{ce,j}$ is the predicted probability that the census enumeration is a correct enumeration.
- $\pi_{m,j}$ is the predicted probability that the census enumeration is a match.

Table 1.
Classification for Dual-System Estimation

System		P Sample: Correctly included in the post-enumeration survey?		
		YES	NO	TOTAL
E Sample: Correctly enumerated in the census?	YES	N_{11}	N_{21}	N_{+1}
	NO	N_{12}	N_{22}	N_{+2}
	TOTAL	N_{1+}	N_{2+}	N_{++}

The data-defined probability predicted the chance that the census enumeration did not have to be imputed. In fact, census processing was able to tell us whether each census enumeration was a data-defined enumeration or not. However, we used the predicted probability of this status to better estimate domains that may have had small numbers of data-defined enumerations.

To calculate final CCFs, we applied a sex-ratio adjustment to adult male and female CCFs. This adjustment aligned adult male-to-female ratios with those from the 2020 Demographic Analysis by age and race groups. More information on this adjustment can be found in Zamora (2022). More information on Demographic Analysis can be found in Jensen et al. (2020).

By summing the final CCFs for the desired estimation domain, we produced the DSE of the population for that domain. We then calculated the net coverage error rate in the following manner:

$$Net\ coverage\ error\ rate\ = \frac{(Census\ total - DSE)}{DSE} \times 100$$

The census total was calculated by summing the target population from a file of edited census data. These data edits ensured that each person on the file had valid values and consistency across characteristics. It also included whole-person census imputations. This sum excluded people located in Remote Alaska areas and those living in group quarters. In general, net coverage error rates were calculated from unrounded numerators and denominators and then rounded. Exceptions were made in tables that include rounded totals. For such tables, we used the rounded numbers to calculate the rates.

Component Estimation for Coverage of People

We estimated four components of coverage:

- Correct enumerations.
- Erroneous enumerations.
- Whole-person census imputations.
- Omissions.

Every enumeration in the census was either a correct enumeration, erroneous enumeration, or whole-person census imputation. Omissions were people who were not correctly counted in the census but should have been. Everyone in the target population was either correctly enumerated in the census or a census omission. The census might have accounted for most of these omissions as whole-person imputations, while others may have been missed altogether. To estimate the rates of correct enumeration and erroneous enumeration, we used the E sample and a design-based estimator.[4]

A whole-person census imputation was a census record for which all the person characteristics were imputed. This occurred when very little information about the household or the people in the household was obtained. For example, a household or proxy respondent might have reported the number of people in the household, but no other information about the people. In such cases, the census imputation methods used characteristics of other people to impute this missing information. The total number of whole-person census imputations was a known quantity and did not require estimation for the components of coverage results. We calculated this total by tallying these imputations on the census files.

To estimate the total number of omissions, we subtracted the estimated number of correct enumerations in the census from the estimated population total (the DSE).

[4] A design-based estimator uses sampling weights to make inferences.

4. ACCURACY OF THE POST-ENUMERATION SURVEY (PES) ESTIMATES

As a sample survey, the PES contained two types of error: sampling and nonsampling. These errors affected the accuracy and precision of the estimates produced by the survey. When possible, their effects should be included in any analysis performed using the survey data. In the following sections we discuss both sampling and nonsampling errors for the 2020 PES. We highlight many of the most noteworthy errors—for a more complete and detailed discussion of the many possible errors, we refer to previous articles (Wolter, 1986; Hogan and Wolter, 1988; Mulry and Spencer, 1991; and Hogan, 2003).

It should also be noted that the 2020 PES survey cycle coincided with the COVID-19 pandemic. This caused delays and errors throughout the life of the survey.

Sampling Error

The PES estimates were based on a sample. As such, they differed somewhat from what would have been obtained if all housing units and people had been included in the survey. This difference is known as sampling error and was estimated from the survey data.

Due to the complex, systematic sample design of the PES and the intricate nature of the dual-system estimator, unbiased, design-based variance estimators do not exist. The PES used the successive difference replication (SDR) method, introduced in Fay and Train (1995) and discussed in U.S. Census Bureau (2014b), to estimate sampling errors. The American Community Survey (ACS) also uses SDR to produce estimates of variance. In fact, the PES used the replicate factors produced by the ACS. We created replicates by multiplying the PES sample weights by the ACS replicate factors within each sample BCU. We did this for both the P and the E samples. Then, for each of the 80 replicates, we performed the same weighting adjustments that were made to the full samples. For the P sample, this included the noninterview adjustment, weight trimming, and unresolved status imputation. For the E sample, we also applied weight trimming and unresolved status imputation, as well as a ratio adjustment to known census totals. This resulted in each person having one final full weight and 80 replicate weights. The variance estimate was then calculated as a function of the difference between the estimate for each replicate and the estimate for the full sample. Finally, we calculated standard errors by taking the square root of these variances. More information on SDR and how it was applied to the 2020 PES can be found in Hill et al. (2019).

When comparing estimates of sampling error from 2020 to those from 2010, it is important to note that the 2010 post-enumeration survey used jackknife variance estimators. Successive difference replication has two main advantages over jackknife and other variance estimators used in the past. First, this method better accounts for the sample design by capturing some of the implicit stratification of systematic sampling. Second, repeating the nonresponse adjustment, imputation, and dual-system estimation for each of the 80 replicates captured variability introduced by these post-processing steps.

The PES performed statistical testing for estimates of net coverage error rates and certain components of coverage. Statements of comparison were statistically significant at the 90 percent confidence level ($\alpha = 0.10$) using a two-sided test. For any PES release, estimated net coverage error rates that were statistically significantly different from zero were identified by an asterisk (*).

Nonsampling Error

For a given estimator, the difference between the estimate that would result if the sample were to include the entire population and the true population value being estimated is known as nonsampling error. There are many kinds of nonsampling error, and, unlike sampling error, they are difficult to quantify. Also, nonsampling errors could be random or systematic. In this document we discuss various nonsampling errors.

Coverage Error in the P Sample

Coverage error refers to differences between the target population and people eligible to be included in the sample. In the P sample, missed housing units or people could cause undercoverage, while undetected duplicates or erroneous inclusions could cause overcoverage. Efforts were taken to remove erroneous inclusions such as duplicates and people outside the target population from the P sample, but some unmeasured amount of overcoverage in the P sample was still present.

To quantify undercoverage in the P sample, we estimated the P-sample omission rate. The national P-sample person omission rate was 13.05 percent (0.86 percent standard error). This omission rate is the ratio of the difference between the national DSE and the weighted P-sample total to the national DSE. The omission rate quantifies how much of the true population was not correctly included in the P sample. The PES aimed to have a P-sample omission rate close to 0. We calculated this rate in the following manner:

$$P - Sample\ omission\ rate = \frac{\widehat{DSE} - \hat{P}}{\widehat{DSE}}$$

where

$$\hat{P} = \sum_{i}^{N} w_i$$

and

- i is a person that was included in the P sample.
- w_i is the final P-sample weight.
- N is the total number of people included on the P sample.

It should be noted that the final P-sample weight, w_i, included the noninterview adjustment. This adjustment shifted weights from noninterviewed housing units to interviewed housing units through propensity modeling and stratification. More information on the noninterview adjustment can be found in Zamora (2022).

Because the PES was used to estimate the true population size, there was no weighting adjustment to correct for coverage errors in the P sample. However, undercoverage in the P sample was not a primary concern because dual-system estimation is robust to coverage errors in each system. If coverage errors in the two systems for dual-system estimation are independent, the dual-system estimates will not be biased because of the coverage errors. Increases in coverage errors in the P sample and census put more reliance on the independence assumption, but would not bias the DSEs, as long as independence between the P and E samples holds. There are many things that could violate this independence assumption. An example of an operational violation of independence would be if an interviewer worked the same block for both the census and the PES. Their prior knowledge of the block from their census work could affect the performance of their PES enumeration work. Causal violations of independence could exist if the fact that a person was captured in the census affects his or her probability of being captured in the PES. More discussion on errors related to violations of independence are in the analysis error section.

Nonresponse Error

Unit nonresponse refers to noninterviewed housing units in the PES. The PES performed a noninterview adjustment to help correct for nonresponse error. Using propensity modeling and stratification, we transferred the weights from noninterviewed households to interviewed households. Note that even with this adjustment, bias might still exist if noninterviewed households were inherently different from interviewed households. For the 2020 PES, the survey relied more heavily on this adjustment than it has in the past because, as seen in Table 2, noninterview rates were higher compared to the previous post-enumeration survey.

To analyze the circumstances around noninterviews, we split them into two categories. The first category represented noninterviews in which no interview was conducted for the housing unit. In the second category, contact was made with either a household member or a proxy respondent, and an interview did take place. However, the information provided by the respondent was not complete enough for survey processing, so we converted these interviews into noninterviews. For the 2020 PES, a larger proportion of noninterviews fell into this second category, contributing to the increase in overall noninterview rate. More information on the noninterview adjustment can be found in Zamora (2022).

Item nonresponse refers to missing data on completed interviews. For dual-system estimation, the key items were the match and enumeration status. Item nonresponse could result if the respondent refused to answer specific questions or if the quality of

Table 2.
Post-Enumeration Survey (PES) Person Interview Response Rates (Unweighted)

Interview outcome	2020		2010	
	Number	Percent	Number	Percent
Total	**161,000**	**100.0**	**171,000**	**100.0**
Interview	114,000	70.8	140,000	81.9
Noninterview	23,000	14.3	5,300	3.1
Interview not conducted	4,900	3.0	2,300	1.4
Interview not sufficient	18,500	11.5	3,000	1.8
Vacant	19,000	11.8	21,500	12.6
Nonexistent	5,200	3.2	4,700	2.8

Note: Counts may not sum to totals shown because of rounding.
Source: U.S. Census Bureau, Decennial Statistical Studies Division, 2020 Post-Enumeration Survey (March 2022 Release) and 2010 Census Coverage Measurement Survey.

Table 3.
Unresolved Rates for Match and Enumeration Status (Unweighted)
(In percent)

Status	2020	2010
Unresolved match status rate	6.4	3.7
Unresolved enumeration status rate	11.6	4.8

Source: U.S. Census Bureau, Decennial Statistical Studies Division, 2020 Post-Enumeration Survey (March 2022 Release) and 2010 Census Coverage Measurement Survey.

information was too low to determine a match or enumeration status. A statistical procedure called imputation was used to assign a match or enumeration status if none could be determined through clerical efforts. In the 2020 PES, the higher amount of missing characteristic data (e.g., age, sex, etc.) and higher rates of incomplete follow-up interviews, relative to the 2010 PES, caused the rates of unresolved match and enumeration status to be higher as well (Table 3). More information on missing data in the PES can be found in Beaghen et al. (2022).

Measurement Error

Measurement error refers to the accuracy of the reported data. One of the features of the PES was that the data collection was performed entirely by in-person interview. In-person surveys are subject to interview effects. While the PES provided high-quality training to all it's field representatives, it was still possible that field representatives misinterpreted their training or did not follow survey procedures as specified. Such errors could lead to added variability or bias in the reported data.

There could also be a social desirability effect related to in-person interviewing. For example, respondents might be less likely to give their honest responses in person, perhaps preferring a written or anonymous response. We allowed for either a household member or a proxy respondent to answer the survey. This alone could invite measurement error into the survey. In general, proxy respondents tend to be less knowledgeable about the sample household than a household member. Often proxy respondents knew general details, like sex and a rough estimate of age, but were unable to provide more accurate details like specific date of birth—which are extremely helpful when matching—or dates when someone moved into or out of a household. Table 4 shows the proxy counts and rates for both the 2020 and 2010 post-enumeration surveys.

Another feature that could affect the accuracy of the data was the length of time between Census Day and the PES Interview Day. Due to the COVID-19 pandemic, some activities in the PES schedule—including the Person Interview operation—had to be delayed. The expanded interval between Census Day and Interview Day increased the potential for recall bias. Recall bias is the phenomenon where, as the interview occurs further from the target event, the respondent may be less likely to remember specific details about the event. These could be details such as specific move dates, the place where they were staying most of the time, or even the birth date of a child. If a respondent couldn't pinpoint whether events like these occurred before, on, or after Census Day, this could create error in the response data.

Table 4.

Completed Interviews by Type (Unweighted)

Respondent type	2020		2010	
	Number	Percent	Number	Percent
Total	**114,000**	**100.0**	**140,000**	**100.0**
Proxy	8,000	7.0	5,200	3.7
Household respondent	106,000	93.0	135,000	96.4

Note: Counts may not sum to totals shown because of rounding.

Source: U.S. Census Bureau, Decennial Statistical Studies Division, 2020 Post-Enumeration Survey (March 2022 Release) and 2010 Census Coverage Measurement Survey.

Further, this phenomenon could become exacerbated when a proxy responded for the household.

Processing Error

Processing error refers to any errors that occur during the editing and coding of response data. For the PES, this could include errors in the way we implemented our data edits, or our computer and clerical matching operations.

The PES employed an edit system to correct for contradictory or implausible reported data. However, the quality of our edits could be compromised if the design of the system was flawed or if the edits were fed unreliable information. For example, if the PES recorded the relationship between two people as parent and child, but the parent's age is lower than the child's, the PES edited the data to correct for this. PES would have based its edit on other information provided, like date of birth. However, if the date of birth was also incorrect for either person, this could create errors within our edit system.

Matching error occurred when the PES incorrectly coded a nonmatch as a match or incorrectly coded a match as a nonmatch. There were numerous activities in the PES that could have led to matching error, including the way we defined the search area for matching, computer matching operations, and clerical matching operations.

During the matching operations, the PES searched the entire nation for matches. However, we restricted the final match determination to those found within the search area for dual-system estimation. In general, as the size of the search area increases, the potential for incorrectly finding a match for a person who was not in the census also increases. For the PES, we defined the search area as the block where the P-sample person was living on Census Day plus the set of surrounding blocks. If, in the census, we found a match to the P-sample person in the search area, then their final status was considered a match, even if the census had the person in a surrounding block rather than the block where the person was found in the P sample. More information on the search area is in Hogan, 2003.

Computer matching could be a source of error if the thresholds used to determine whether two different person records referred to the same person were not set properly. One benefit of the PES was that during clerical matching, technicians and analysts reviewed all matches and nonmatches from computer matching, removing false matches and adding new matches. However, there still could have been false matches because of clerical error. While we tried to mitigate clerical matching error with training, practice, and ultimately a qualifying test, there could have been errors in the training, or the clerical matching staff may not have followed procedures correctly. The PES clerical matching operations also included a robust quality control process where each matching technician's work was routinely reviewed by an expert analyst.

Measurement errors and item nonresponse could also contribute to matching errors. For example, if a person's date of birth or name was recorded incorrectly, or not at all, the PES might not have been able to match that person to the census enumeration.

Analysis Error

Analysis error, also called adjustment or estimation error, arises from various efforts after data collection, usually to improve inference and correct for other errors in the survey life cycle. The PES estimation process used many statistical techniques, such as weighting adjustments and imputation, to correct for errors in the data. Although these techniques were intended to improve the data, they may also have introduced some errors.

The PES employed a noninterview weighting adjustment that applied propensity stratification to correct for unit nonresponse (Zamora, 2022). Errors in the propensity models or creation of cells could add variance or bias to DSEs.

Imputation was used to reduce errors resulting from item nonresponse (Zamora, 2022). This included imputing person characteristics, as well as match and correct or erroneous enumeration status. Violations of assumptions underlying the imputation procedures could add systematic and random errors to coverage estimates. Estimates of sampling error should include many of the random errors resulting from imputing P-sample match status and E-sample enumeration status; however, errors from characteristic imputation and systematic bias in the imputation procedures were not estimated. Nevertheless, well-researched and robust imputation procedures were used to fill in missing data in the PES. The imputation models fit the data very well and likely reduced the impact of item nonresponse.

Some estimators are inherently biased. For example, it is well known that the ratio estimator, as a nonlinear estimator, is biased. This means that it differs on average from the ratio it is estimating. This bias becomes very small as the sample size increases, so it usually is not a concern. Like the ratio estimator, the dual-system estimator is also biased. Fortunately, the PES sample sizes are large enough that the bias of the synthetic DSE is negligible.

Synthetic error is the difference between the population estimate calculated from the synthetic models and the true population total. For dual-system estimation, synthetic estimation error could have occurred if we produced estimates for domains that were not included as covariates in our models for dual-system estimation. For the 2020 PES, we tried to mitigate this error by ensuring that all desired estimation domains were included in the DSE models. For example, in the 2020 PES we included Tenure as a covariate in the DSE models so that we could produce estimates for owners and renters.

A final source of analysis error could arise from violations of the assumptions on which dual-system estimation is based. Mulry and Spencer (1991) and Wolter (1986) discuss many of the assumptions and models supporting dual-system estimation. First, although dual-system estimation did not require complete coverage and response from the census and the PES, it relied on the statistical independence of the enumerations between the two. Violations to statistical independence could arise from correlation bias. Correlation bias occurs when the probability of being included in one system influences the probability of being included in the other system.

Correlation bias also exists when there is heterogeneity in the capture probabilities of similar individuals, that is, when similar people have different probabilities of being included in either the census or the PES (Sekar and Deming, 1949; Wolter, 1986; and Mulry and Spencer, 1991). For example, in previous post-enumeration surveys, it was noted that some adult males were systematically missing from the census and the PES at higher rates than females (Bell, 1993).

The 2010 PES and the 2020 PES tried to reduce heterogeneity of capture probabilities by modeling specific capture probabilities for each person. However, missing covariates or interaction terms in the models could result in heterogeneity and add to the variance or the bias of the DSEs.

In conclusion, while every survey must deal with a multitude of errors, and the PES is no different, we implemented many measures to mitigate the impact of these errors on our estimates. The PES estimates provide helpful insights about the quality of the 2020 Census and should be useful when informing plans for the 2030 Census.

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