Cash or card? A structural model of payment choices*

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Abstract

We use a large granular dataset to analyze the households' choice between cash and card payments. Empirically, both the *size of the transaction* and the amount of *cash on hand* appear as significant covariates of the payment choice. We unveil a novel interaction between these two variables: the critical size for a card purchase depends on the amount of cash on hand. We present a tractable model of payment choices, featuring non-universal acceptance of cards by merchants, and a random expenditure flow. The model generates a precautionary motive for holding a cash buffer: cards are used to avoid "running out of cash", accounting for the interaction discussed before. We use a calibrated version of the model to quantify the benefits of card ownership, the welfare costs of imperfect card acceptance by merchants, and to identify conditions under which a *cashless economy* emerges.

Keywords: *cash management, payment choices, inventory model, card payments.*

JEL classifications numbers: *E41, E42, D14.*

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1 Introduction

Advances in information technologies and digitization change the payment behavior of households and raise interesting questions on the welfare benefits of new technologies, and the future of cash (see Trütsch (2020), Shy (2023), and Nocciola and Zamora-Pérez (2024)). We present new evidence on means-of-payment choices in the euro area, drawn from surveys conducted by the European Central Bank between 2015 and 2024. The transaction-level data shows that the households' *choice* on whether to pay with cash vs card, in situations where both options are feasible, deviates from the predictions of simple means-of-payment models. First, for a substantial fraction of individuals the largest reported cash payment is bigger than the smallest card transaction occurred on the same day, a behavior that contradicts the simple *threshold-rule* prediction by Whitesell (1989). Second, card payments are often chosen when households have sufficient cash to carry out the transaction, contradicting *cash burns* policies that prescribe using cards only after running out of cash, as in Alvarez and Lippi (2017). Moreover, the data reveals a novel pattern in payment behavior: card usage becomes more likely as the size of the purchase approaches the level of cash on hand, i.e., when the residual money holdings in case of a cash payment are low. The latter is consistent with a precautionary motive: a cash buffer provides insurance for the transactions where cards cannot be used.

We propose a dynamic model of cash management to interpret the facts. The model features a stochastic expenditure flow and imperfect acceptance of cards by merchants. The agent chooses the frequency and size of cash withdrawals, and can settle her purchases with cash or a with a card. As customary in inventory-theoretic models, cash withdrawals entail a fixed cost; we also assume that using the card entails a fixed cost per-purchase.[1] The model solution prescribes the optimal payment policy: the agent holds a precautionary stock of cash to avoid paying excessive card fees, as well as to insure against shopping trips in which cards are not accepted. If the cost of using cards relative to cash is small, the agent uses the card even when cash on hand is sufficient, in order to preserve her cash buffer. The optimal policy shares features of Whitesell (1989) – namely, for a given level of cash balances, the

[1] This cost represents fees and the non-pecuniary costs of using cards, among which privacy concerns.

agent follows a transaction-size threshold policy – and of Alvarez and Lippi (2017) – namely, that cash is always employed to settle small-value transactions. The optimal policy features a novel interaction between the amount of cash on hand and the size of the purchase: the transaction-size threshold above which the agent uses cards depends on the amount of cash held before the payment occurs.

Our analysis rests on three important modeling ingredients. First, the random timing and sizes of expenditures create the possibility that the agent may find herself without enough cash to carry out a purchase, giving rise to a precautionary demand for cash, as in Telyukova (2013).[2] Second, the choice between cash versus card payments is modelled sequentially, so that the agent chooses whether to use cash or card at each moment, conditional on the purchase size and her cash holdings. This is similar to Alvarez and Lippi (2017) and Briglevics and Schuh (2021), and differs from the classic analysis by Lucas and Stokey (1987) and Whitesell (1989) where the agent simultaneously chooses the mix between cash versus card payments over a fixed time period.[3] Third, the setup features (exogenous) imperfect acceptance of cards by merchants. This assumption boosts the precautionary motive for holding a cash buffer, a feature that is strongly apparent in the data.

We calibrate the model by matching selected moments on cash management and payment choices for the euro area households, computed from diaries collected by the ECB in 2023-2024. We use the calibrated model to inspect features of the current payment system and develop some counterfactual analyses. The calibrated model reveals an overall annual cost of managing transactions that is remarkably small (around 15 euros for the average household), suggesting that the payment system imposes a relatively small burden on the households' budgets. We analyze a counterfactual scenario where households can only use cash, and find that the annual cost of managing transactions is about 50 euros, i.e. that the value of a payment card is around 35 euros per year, highlighting the quantitative importance

[2]The assumption contrasts with the standard inventory models where consumption follows a continuous path, see Miller and Orr (1966), Eppen and Fama (1969), and Alvarez and Lippi (2009), among others. Technically, consumption follows a compound Poisson process, see Perera and Sethi (2023) for a review. Examples of cash management models including (or exclusively making use of) compound Poisson expenditure include Beckmann (1961) and Bar-Ilan, Perry, and Stadje (2004).

[3]In those classic models one cash withdrawal occurs in every period, and all cash is spent. No purchase opportunities are ever missed and statistics such as the size and frequency of withdrawals are exogenously determined by the model's time period length.

of cards for consumers' welfare. We also show that a complete ban of cash would increase the cost of managing consumption transactions by around 60 euros per year for the average consumer.[4] We estimate that the imperfect acceptance of cards by merchants is costly for households: under near-universal acceptance of cards, the annual cost of managing cash and settling transactions would decrease by almost 75% (from 15 to 4 euros per year). We use the model to identify the conditions for a cashless economy to emerge. The analysis shows that cash is quite resilient: increasing the rate of card acceptance from the current level of 89% to *near-universal* (99%) does not eliminate cash usage; the share of cash expenditures (over total consumption) falls substantially but remains non-negligible. Under near-universal acceptance, a cashless economy only emerges if card payments become as cheap as cash ones. Given the current card acceptance rate, even cards becoming substantially cheaper than cash would *not* lead to a cashless economy, as consumers would still hold a cash buffer to avoid missing a purchase.

1.1 Related literature

Several studies use micro-level evidence such as payment diaries or stores' transaction data to study the determinants of consumers' payment method choices (see Shy (2023) for a review of the literature). A first set of papers establishes a link between the payment method decisions and the size of the purchase. Exploiting grocery store data, Klee (2008) finds that cash is mainly used for small-sized purchases, while card payments are prevalent when the value of the sale increases. Similar results are obtained by Wang and Wolman (2016) leveraging on scanner data from two billion retail transactions, and by many other studies. A second relevant determinant of cash/card choices is the amount of cash on hand at the moment when the transaction is settled. The papers that analyzed the relationship between cash holdings and payment choices consistently found that the likelihood of cash usage increases with the level of cash holdings.[5] A third potential determinant of payment choices by individuals are also supply-side factors such as limited acceptance of means of payments:

[4]A ban on cash is endorsed by Rogoff (2017); see Alvarez, Argente, Jimenez, and Lippi (2022) for a critical assessment of this proposal using Mexican data on crime and cash usage.

[5]See Arango, Huynh, Fung, et al. (2012), Bouhdaoui and Bounie (2012), Huynh, Schmidt-Dengler, and Stix (2014) and Bagnall et al. (2016).

several studies (see Arango, Huynh, and Sabetti (2015) and Huynh, Schmidt-Dengler, and Stix (2014), among others) showed that the probability of card acceptance by merchants affects means of payments decisions by consumers. Moreover, a number of studies (see for example Bagnall et al. (2016)) documented a relationship between payment choices and cash management decisions, finding a positive association between cash usage, the frequency and size of withdrawals, and average cash holdings. We contribute to this empirical literature using a rich payment diary dataset for the euro area over the years 2015 - 2022 and highlight a novel finding: households' choices to pay with cash or card are affected by how large the incoming transaction is *relative* to the amount of cash holdings.

A few theoretical studies analyze the households' payments choice using the standard cash management model a' la Baumol (1952) and Tobin (1956) (BT from now on). Whitesell (1989) includes a non-degenerate distribution of transaction sizes in the BT model, as well as a choice among cash and card payments. In this model, it is optimal to pay by cash whenever the size of the transaction is smaller than a given threshold, and to pay using cards otherwise (*transaction size threshold* policy). Alvarez and Lippi (2017) abstract from transaction size heterogeneity and present a dynamic model where payment choices only depend on the level of cash holdings, showing that cards are used only when the agent does not have enough cash at hand (*cash burns* policy). Notice that the predictions of both these models are broadly consistent with the above-cited empirical findings on the relationship of payment choices with transaction sizes and cash holdings. A related analysis by Briglevics and Schuh (2021) estimates a discrete choice model in which the agent's decision on how to pay depends both on the size of the transaction and on the amount of cash held, using US payment diary data. In recent work, Huynh, Shcherbakov, and Stenzel (2025) estimate a dynamic cash inventory model at the consumer level using Canadian diary data.

1.2 Structure of the paper

The paper is organized as follows. Section 2 presents our empirical analysis and highlights new stylized facts on the interplay between cash management and payment choices. Section 3 outlines our theoretical framework and discusses the properties of the policy followed by the agent. We show how the model's solution maps into observable cash management and payment choice statistics. In Section 4 we discuss our calibration strategy, discuss the results, evaluate the model fit and perform a welfare analysis. We then move to applications. In Section 5.1 we use our calibrated model to evaluate the welfare benefit of having a payment card. In Section 5.2 we quantify the cost for households stemming from imperfect acceptance of cards, and study a counterfactual scenario with near-universal acceptance by merchants. In Section 5.3 we assess the resilience of physical cash as a means of payment. Section 6 concludes.

2 Stylized facts about households' payment behavior

This Section presents the data used in the paper and the main empirical patterns that motivate the analysis. In Section 2.2 we compare the predictions of existing models of payment choice with evidence drawn from transaction-level data. In Section 2.3 we illustrate new facts on payment choices by households and on the relationship between card acceptance rates and cash management behavior.

2.1 Data sources

We use payment diaries and questionnaires from two ECB surveys: i) the *Survey on the use of cash by households in the euro area* (SUCH from now on), that contains data from 2015 and 2016, ii) the first three waves of the *Study on the payment attitudes of consumers in the euro area* (SPACE I, II and III from now on), carried out in 2019, 2021-22 and 2023-24, respectively.[6] Individuals participating in the surveys are asked to record in a diary their payments on a given day.[7] For each transaction the diary records the type of store, the amount paid and the payment method employed (cash or a cashless option, that we broadly label as *card payments*).[8] For each purchase, respondents are also asked if alternative payment methods were accepted

[6]Although the surveys were conducted in different years and changed name over time, they utilize a nearly identical diary-based methodology. This ensures that the variables we rely on are comparable across the entire 2015–2024 sample period.

[7]Payments include both point-of-sale (POS) transactions, i.e., normal purchases in stores, and payments made to other individuals (P2P), such as charity or transfers to other family members, friends and colleagues. We disregard online payments as they are almost always settled using cards.

[8]We refer to all payment methods excluding cash as *cards*. These include debit cards, credit cards (both with and without a contactless option), mobile payments, credit transfers, bank cheques and other payment types. Figure A.1 in the Online Appendix displays how often each of these payment instruments is used within every wave.

Table 1: Cash management and payment choices by households: summary statistics.

	Time period			
	2015-16	2019	2021-22	2023-24
Expenditure flow				
Daily expenditure (EUR)	34	46	64	61
Size of payment (EUR)	19	28	33	32
N. daily transactions	1.8	1.7	1.9	1.9
Households' cash management				
Cash holdings (EUR)	60	83	85	82
Withdrawal size (EUR)	70	90	108	96
Pr(Withdraws cash)	0.11	0.13	0.22	0.26
Sellers' acceptance of payment methods				
Card accepted	0.72	0.80	0.85	0.89
Features of transactions				
Forced card	0.09	0.14	0.19	0.16
Forced cash	0.28	0.20	0.15	0.11
Unforced (both options possible)	0.63	0.66	0.66	0.73
Households' payment method choices				
Pr(Card)	0.25	0.32	0.44	0.49
Pr(Card | Unforced)	0.26	0.27	0.37	0.45
Number of respondents	64,214	40,182	39,459	40,710
Number of transactions	117,487	67,765	76,320	77,201

Note: All rows display sample averages. The daily expenditure and number of daily transactions are lower bounds for their true values as respondents can report at most eight purchases on the payment diary. The amount of cash holdings is that reported at the start of the diary day. The probability of a cash withdrawal is relative to the day of the survey. Online payments are excluded. Only respondents with access to cards are considered. The final sample includes a total of 338,773 transactions (with cash or cards) performed by 184,565 individuals.
Data from ECB payment diaries: SUCH (2016) and SPACE (2019, 2021-22 and 2023-24).

at the point of sale. The level of cash holdings at the start of the diary day, as well as any other cash inflow that occurs during the day are reported as well: in particular, respondents report whether they withdrew cash (from ATMs, via cashback, or simply by moving coins and banknotes held at home to their wallets) or received it from others (as cash income, or by family and friends). This information enables us to back up the level of cash holdings before each transaction takes place, for a large set of participants.[9] Finally, respondents answer a survey questionnaire where they provide additional information on their cash management and payment habits, as well as on a large set of demographic characteristics.

The data enables us to take a close look at European households' decisions concerning

[9]See Section A.2 of the Online Appendix for the technical details on the data cleaning process and on the derivation of additional information from the original datasets.

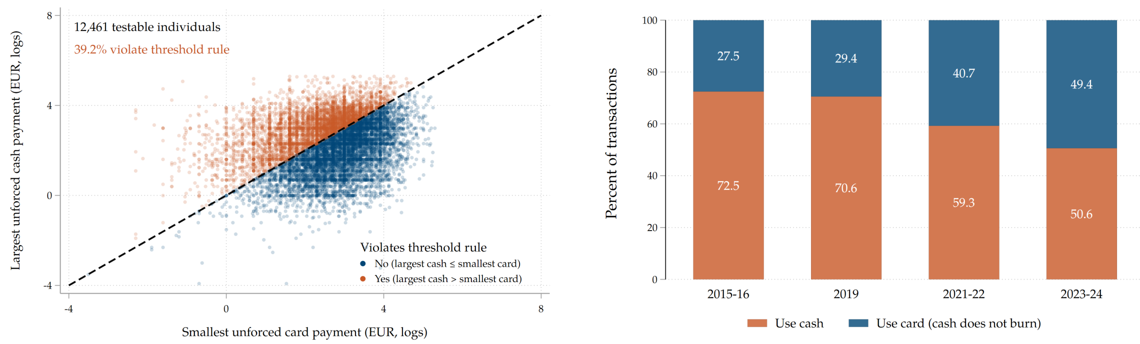
payment method's adoption and usage (in particular, whether to hold cards or not, and when to use them), as well as on cash management policies (frequency and size of cash inflows and outflows) across the 2015-2024 period. A key feature is that having combined information on the level of cash holdings and the set of payment methods accepted in the point of sale, we can pin down the set of available payment options (*payment choice set*) for each transaction. This enables us to distinguish between payment choices that are *forced*, e.g., paying using the card because cash on hand is insufficient, from those that are *unforced*. Unforced transactions are those in which both cash and card payments are possible, i.e., in which the amount of cash holdings is larger than the purchase size, the merchant accepts card and cash payments, and the consumer has access to a payment card. It is evident that unforced transactions are important to identify the determinants of individual payment choices.[10] In Table 1, we display selected summary statistics across the four waves for the subsample of respondents with access to cards (around 99% of consumers). The Table describes the expenditure flow of households during the diary day and cash management behavior by households: we report the average cash holdings, the proportion of respondents that withdrew cash during the day, as well as the average withdrawal size.[11] The middle panel of the Table depicts the acceptance of payment methods by sellers. Card acceptance by merchants increased during this period. In the bottom of the Table we display the fraction of transactions in which cash and cards were available options, as well as the share of unforced transactions. This combines the supply-side acceptance decision by merchants with the buyers' choices. The share of *unforced* transactions has slightly increased over the sample period from around 60% to more than 70% of total transactions. The total fraction of card payments went up throughout the sample period, and so did the share of unforced transactions settled using cards (from 25% to about 45%).

[10]Most studies in the literature instead either disregard the fact that one can pay by cash only when the size of the transaction is smaller or equal than current cash holdings, or operate under the assumption of full acceptance of all payment methods, or both.

[11]The notable increase in daily expenditures and cash holdings over time is largely attributable to changes in the composition of the sample and in the timing of data collection within the year. We estimate our structural model using the data from the 2023-24 survey.

Figure 1: Patterns of payments behavior.

(a) Evidence on the *TS threshold* policy. (b) Evidence on the *cash burns* policy.



Note: An *unforced payment* is one where both cash and card were viable payment options. In Panel (a), each dot corresponds to one respondent. In total, we have 12,461 individuals who report both an unforced cash payment and an unforced card payment during the diary day. The dashed line is the 45 degree line. Panel (b) displays the distribution of payment choices for *unforced* transactions. We say that *cash does not burn* when a card payment is preferred to cash.
Data from ECB payment diaries: SUCH (2016) and SPACE (2019, 2021-22 and 2023-24).

2.2 Patterns of payment choice: data vs models

Two main mechanisms have been proposed to explain how households choose between cash and cards. A first hypothesis is that individuals choose how to pay depending on the size of the transaction. A second one is that consumers use either cash or cards depending on the amount of cash they have on hand. We compare the implications of these theories with observed behavior.

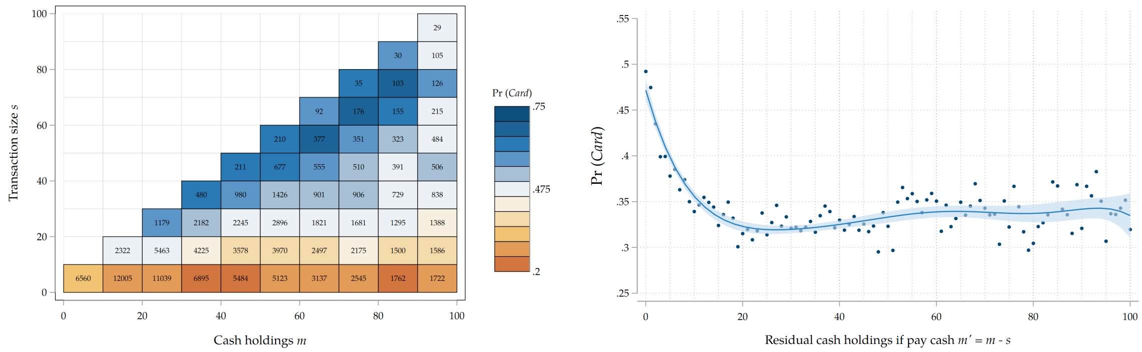
Transaction-size threshold policy. Some models emphasize the role played by the size of the transaction (which we denote by s) as a determinant of consumers' payment choices (Prescott (1987), Whitesell (1989), Freeman and Kydland (2000)).[12] Under the assumption that cash payments incur costs that are proportional to the size of the transaction, while cards required a fixed per-transaction cost, these papers derived optimal payment policies characterized by *transaction-size thresholds*: individuals settle using cash the expenditures which are smaller than some threshold transaction size ($s \leq \underline{s}$), while they exploit cards for large-sized purchases ($s > \underline{s}$). Support for this theoretical prediction has been provided by many empirical papers that find a negative correlation between the size of transactions faced

[12] Wang and Wolman (2016) offer a summary of this literature, which they refer to as the *threshold framework*.

and the probability of cash usage (Klee (2008), Wang and Wolman (2016)). However, the presence of a negative association is a rather qualitative test of the theory. Our data enables us to see if households actually adopt such threshold policies when deciding on how to pay: given that we observe multiple transactions for each individual, and that we can pin down the payment alternatives available at each transaction, we can compare the largest unforced cash payment and the smallest unforced card payment of respondents. Figure 1a reveals that support for threshold-based policies is quite weak: among the subset of households that reported both an unforced card payment and an unforced cash payment, around 39% of individuals explicitly violate the simple transaction-size threshold rule. This is contrast with the model's predictions: even allowing for individual-specific thresholds $\underline{s}_i$, under a transaction-size threshold rule all dots should lie below the 45 degree line.

"Cash burns" policy. Other models of payment choices focus on the level of cash holdings at the moment in which the transaction takes place (which we denote by m). Motivated by empirical findings showing that consumers are more likely to use cash as a means of payment when cash balances are larger,[13] Alvarez and Lippi (2017) outline an inventory model augmented with a means of payment choice. In their setup, it is optimal to use cards only when $m = 0$, i.e., when the agent has no cash on hand at all: whenever she has cash, she uses it, as if *cash burns* in her hands. A generalization of such policies to a setting with lumpy purchases is proposed by Arango-Arango et al. (2018), that present a model where the agent uses cash whenever they she has enough ($s \leq m$) and cards otherwise. The *cash burns* policy, if taken at face value, implies that cash is used whenever $s \leq m$: in other words, the share of *unforced card payments* is negligible. Figure 1b shows that this is not the case. Across all survey waves, a substantial fraction (27 to 49%) of unforced transactions are paid by card; such a "violation" of the simple *cash burns* policy appears to be getting increasingly common over time. Therefore, a theory in which cards are a residual means of payment, employed only when there are no other viable options, seems at odds with this evidence.

Figure 2: Share of card payments for different m, s and $m' = m - s$.



Note: The left panel displays the share of payments settled using cards for bins defined in terms of cash holdings at payment (m) and transaction size faced (s). Numbers denote the number of observations falling in each bin. We focus on transactions where m and s are smaller or equal than 100 euros to avoid having cells with a very small number of observations (different sets of transactions/cash holdings are considered in Appendix, see Figures A.3 and A.4 in the Online Appendix). The right panel displays the shares of households paying using cards for bins defined in terms of cash holdings remaining in case the agent settles the payment using cash (*implied residual cash holdings* $m' = m - s$). A nonparametric fit ($h = 10$) with 95% confidence intervals is overlaid to the plot. Only unconstrained transactions are considered, and transactions with $m = s$ are omitted.
Data from ECB payment diaries: SUCH (2016) and SPACE (2019, 2021-22 and 2023-24).

2.3 More evidence on payment behavior

In this Section we document a new pattern concerning payment choices. In the left panel of Figure 2, we display how the payment method choice (cash vs cards) varies as a function of the *amount of cash* balances and the *size of the purchase*. The graph shows the proportion of transactions settled using cards, as opposed to cash, for different bins defined by cash holdings m and purchase size s. We focus on *unforced* payments, by excluding both the transactions in which cash is not a feasible payment method ($s \geq m$ or cash not being accepted) and those in which card payments are not available (the shop does not accept cards or the individual does not have access to a card). Focusing on unforced payments is crucial as it nets out the mechanical effect of m and s on payment choices through their impact on available payment options.[14]

The Figure reveals that, for a given level of cash holdings m, the probability of using

[13]See for example Stix (2004), Arango, Huynh, Fung, et al. (2012), Huynh, Schmidt-Dengler, and Stix (2014) and Arango, Huynh, and Sabetti (2015).

[14]Notice that both estimated effects are likely to be biased upwards when payment choice sets are not exactly observed, for two reasons. First, the probability of a card being accepted by merchants is increasing in the size of the transaction. In Figure A.2 in the Online Appendix, we show that this phenomenon is evident in our sample as well. Second, when transactions are larger it is more likely to have insufficient cash to settle the purchase.

cards rises as the size of the transaction s increases. This result is consistent with previous empirical findings for the US and Canada (Klee (2008), Wang and Wolman (2016), Wakamori and Welte (2017)). Moreover, for a given purchase size s, individuals are less likely to use cards to settle a purchase when cash balances m are larger: this finding is in line with empirical evidence for several countries (Stix (2004), Arango, Huynh, Fung, et al. (2012), Huynh, Schmidt-Dengler, and Stix (2014), Arango, Huynh, and Sabetti (2015), Bagnall et al. (2016)).[15]

These facts offer strong evidence that both the transaction size s and the amount of cash holdings m affect individuals' payment choices. Questionnaire data available in the SUCH survey further corroborate this claim. Respondents were asked the question "*Which of the following influences your decision to pay with cash or card or other non-cash payment methods?*". As shown in Figure A.5 in the Online Appendix, their responses align closely with our empirical findings based on observed behavior: the level of cash holdings and the size of the transaction are the most frequently cited factors, each mentioned by over 50% of respondents as key drivers of their payment method decisions. This evidence reinforces our argument that payment behavior is state-dependent. In particular, differences in payment method choices arise not only from time-invariant heterogeneity across consumers (e.g., demographics), but also – importantly – from within-consumer variation driven by fluctuations in m and s across transactions.[16]

The left panel of Figure 2 also illustrates that when the transaction size s is very close to m (in the graph, these transactions lie in the area just below the 45° line) cards are employed more often. We look at this phenomenon more closely in the right panel of the Figure, where we display the proportion of card payments for different levels of *implied residual cash holdings* (residual cash holdings in case of a cash payment, i.e., $m' = m - s$). It shows that the

[15] In principle, these results could be driven by selection: individuals who prefer to use cards might have on average little cash with them and purchase more expensive goods. To rule out this possibility, we run linear probability models in where we add a large set of demographic and transaction-specific controls; we also include random effects exploiting the panel dimension of our data. We find statistically significant relationships between the size of purchases/the level of cash balances and payment method choices (results are reported in Section A.3 of the Online Appendix). On average, a 10 EUR increase in payment size s is associated with a 4.1pp (8%) increase in card usage probabilities, while a 10 EUR increase in cash holdings m is associated with a 0.6pp (2%) decrease in the probability of using cards.

[16] Among the respondents to SUCH/SPACE that report at least 2 transactions, x% used both cash and cards, suggesting that one should strongly reject the hypothesis that payment choices only vary across, but not within, consumers.

probability of card payments rises as $m' = m - s \to 0$. Households avoid using cash when doing so would lead to a near depletion of their money holdings, suggesting the existence of a precautionary motive to hold a buffer stock of cash: consumers anticipate that cash may be needed for transactions taking place in stores where payment cards cannot be used.[17]

3 An inventory model with a cash vs card choice

In this Section we present an inventory model of cash management with a choice between cash and card payments. We begin by describing the setup and the sequence problem faced by the agent. In Section 3.1 we present the Bellman equation and characterize the optimal policy. In Section 3.2 we compute the model-implied observable statistics, and in Section 3.3 we compare the predictions of our model with previous theoretical and empirical work.

We consider an agent who finances an expenditure stream given by a compound Poisson process, whose cumulative value at time t is given by $e(t) = \sum_{i=1}^{N(t)} s_i$, where $s_i > 0$ is the size of the $i - th$ purchase, captured by a (continuous) random iid variable with cdf $F(s)$, and $\{N(t) : t \geq 0\}$ is the counter associated to a Poisson process with rate λ. We make this assumption to model a realistic expenditure flow, with purchase opportunities arising at random times $\{T_i\}$ and transactions having discrete sizes $\{s_i\}$. Agents can pay for their purchases using either cash or a payment card.[18] Using cards entails a fixed fee κ, independent of the value of the purchase and meant to capture both monetary fees and the non-pecuniary costs of using cards instead of cash, such as e.g., habit formation in payment behavior and privacy concerns. We do not take a stand on the sign of κ, allowing for $\kappa > 0$ to reflect the costs of card usage (monetary costs, privacy costs) or alternatively $\kappa < 0$ to reflect the benefits of a card payment (e.g. safety, convenience).[19] We assume that cards are accepted in a fraction

[17] Eschelbach and Schmidt (2013) find a similar pattern in German payment diary data, attributing it to precautionary behavior by consumers who want to avoid using the entire amount of cash in their wallets, as they might need it for future purchases. In Section A.3 of the Online Appendix we present regression output from linear probability models (adding a full set of controls to take care of selection) that corroborates this claim: we show that the positive effect of an increase in s on the probability to use cards becomes larger in magnitude as m decreases, consistently with individuals timing their use of card payment to avoid settling with cash those large transactions that would drain their balances. We corroborate our interpretation that imperfect card acceptance by merchants is an important driver of such precautionary motive in Section A.4 of the Online Appendix.

[18] In the model we use the word *card* to denote any cashless payment option, as we did in Section 2. Even though each non-cash payment method has different properties (e.g. debit vs credit cards), our model abstracts from such differences.

[19] Using shopping diary data, van der Cruijsen, Hernandez, and Jonker (2017) show that the habit of paying

$\phi \in (0,1)$ of stores, which is exogenous and independent of the value of the purchase.

Let m denote the level of cash balances. Holding m units of cash entails an opportunity cost Rm, while adjusting cash holdings through a cash withdrawal (w) has a fixed cost $b > 0$. Cash balances must be larger than the size of the transaction in order to settle a purchase with cash ($m > s$). When cash on hand is insufficient to carry out a purchase and the store does not accept cards, the agent cannot consume: we assume that this event entails a cost u, independent of the size of the purchase missed.[20] Letting ρ be the discount rate, the agent's problem is described by

$$\begin{aligned} v(m) = \min_{\{(\tau_j, w_j)\}_{j=0}^{\infty}, \{\alpha_i\}_{i=0}^{\infty}} \mathbb{E} \Bigg(& \int_0^{\infty} e^{-\rho t} R\, m(t) dt + \sum_{j=0}^{\infty} e^{-\rho \tau_j} b \\ & + \sum_{i=0}^{\infty} e^{-\rho T_i} \Big(\kappa \cdot \mathbf{1}(\alpha_i = \text{card}) + u \cdot \mathbf{1}(\alpha_i = \text{lose}) \Big) \Bigg| m(0) = m \Bigg) \\ \text{subject to} \quad & m(t) = m(0) + \sum_{\tau_j \le t} w_j - \sum_{T_i \le t} s_i \cdot \mathbf{1}(\alpha_i = \text{cash}) \end{aligned} \tag{1}$$

where $v(m)$ is the value function representing the expected discounted costs as a function of current cash holdings m. The agent controls the sequence of withdrawal times $\{\tau_j\}_{j=0}^{\infty}$ and withdrawal amounts $\{w_j\}_{j=0}^{\infty}$, as well as the payment method decisions $\{\alpha_i\}_{i=0}^{\infty}$ at each purchase arrival time T_i, when the agent chooses $\alpha_i \in \{\text{cash}, \text{card}, \text{lose}\}$: paying with cash (if $m \ge s_i$), paying with card at cost κ, or losing the purchase at cost u. Cash withdrawals incur a fixed cost b. The constraint describes how cash-withdrawals w_i and cash-expenditures s_i affect the evolution of $m(t)$.

with cash is a major driver of consumers' payment behavior at the point of sale in the Netherlands. Drawing on data from the 2021-22 SPACE survey questionnaire, Nocciola and Zamora-Pérez (2024) find that privacy concerns, the speed of settlement, and budget control features are major drivers of preferences for cash. In principle, it could instead be that using cards entails a fixed *benefit* with respect to using cash ($\kappa < 0$), as the former are perceived as safer (Schuh and Stavins (2016)), easier to use and are possibly more convenient (due to loyalty rewards and cashback programs, see Ching and Hayashi (2010)).

[20] We assume that u is large enough that the agent always prefers to complete transactions if she can do so.

3.1 A characterization of the optimal payment policy

Consider an agent with cash balances m. Define

$$m^* = \arg\min_m v(m), \tag{2}$$

and let $v^* = v(m^*)$. The value function obeys the Bellman equation

$$\begin{aligned}\rho\, v(m) = \min\Big\{\rho(v^* + b)\ \ ,\ \ & Rm + \lambda\,(1 - F(m))\,(\phi\kappa + (1-\phi)u) + \\ & + \lambda \int_0^m \Big(\phi \min\Big\{v(m-s) - v(m), \kappa\Big\} + (1-\phi)(v(m-s) - v(m)\Big)\, dF(s)\Big\}.\end{aligned} \tag{3}$$

The outer min operator describes the agent's choice between paying the cost b and refilling her wallet, versus choosing not to withdraw cash. In the latter case, with probability $1-F(m)$ the incoming purchase is too large to be paid in cash, namely $s \geq m$: if the store accepts cards, which happens with probability ϕ, a cost κ is paid and a card payment occurs. Otherwise the purchase is lost and the agent incurs a loss of size u. When the size of the incoming purchase is smaller than m and the store accepts cards, the agent faces a nontrivial payment choice, represented by the inner min operator. If she uses cash, the state jumps to $m - s$. Alternatively, the agent pays the fixed cost κ, uses the card and the cash balance is unchanged. When the store does not accept cards, cash is used and the value function changes from $v(m)$ to $v(m-s)$.

Next, we discuss the agent's optimal policy. This is given by two decision rules: a *withdrawal policy*, determining whether (and how much) to withdraw for any value of current cash holdings m, and a *payment policy*, which determines whether to use cash or cards to settle an expenditure of size s when having $m \geq s$ units of cash at hand.

Withdrawal policy. We make the following simplifying assumption that holds under a wide range of parameters and enables us to provide a sharper description of the model's solution:[21]

[21] The model setup is close to the stochastic, continuous-review inventory model for the case of compound Poisson demand, for which the optimal policy belongs to the class of impulse-control trigger-target policies $(\underline{m}, m^*)$ often called Ss policies, see Perera and Sethi (2023). The lack of a diffusion or drift component makes the continuous-time problem mathematically close to a discrete-time one, as it can only be optimal to adjust after a negative jump in the state occurs. Our model departs from the standard setup as the agent has the possibility to finance part of the consumption stream using cards. As the optimality of trigger-target policies in such a setting has not been proven, we check their optimality in our context numerically. Numerical experiments suggest that

Assumption 1. *There exists* $\underline{m} \geq 0$ *such that* $v(m) = v^* + b$ *for any* $m \leq \underline{m}$*, and* $v(m)$ *is continuous and strictly decreasing on* $[0, m^*]$.

Assumption 1 posits that the optimal withdrawal policy is of the Ss form: it is characterized by a trigger value $\underline{m}$ and a target value m^*, such that a cash-withdrawal takes place if $m \leq \underline{m}$, and the cash balance is reset to $m^* > \underline{m}$. The value function v is flat in the withdrawal region, namely $v(m) = v^* + b$ for $m \leq \underline{m}$. This is the highest level that the value function takes, i.e. the most costly position the agent experiences. The value function is (weakly) decreasing over $(\underline{m}, m^*)$. In Figure 3a we display the value function $v(m)$ and the optimal withdrawal policy, described by $\underline{m}$ and m^*. We also define the value $\widetilde{m}$, which is the level of cash holdings that satisfies $v(\widetilde{m}) = v^* + b - \kappa$. It is immediate that the card will not be used if $m < \widetilde{m}$, since using the card would give a value higher than $v^* + b$. Notice that if $\kappa > 0$ then $\underline{m} < \widetilde{m}$, as discussed below. Figure 3a shows that the optimal policy features a positive trigger value $\underline{m} > 0$, i.e., the agent withdraws cash before emptying her wallet. This happens because the model features a precautionary motive for holding cash: the agent needs to insure against shopping trips in which merchants might not accept cards (which might entail a cost u).

Payment policy. Under Assumption 1, it is possible to characterize the payment policy in detail. Let $p(m, s) = \{0, 1\}$ denote which payment method is employed when facing a purchase of size s and having m units of cash balances on hand, conditional on cards being accepted, with $p(m, s) = 1$ denoting the choice of the card payment. For $s \leq m$, we have

$$\begin{aligned} p(m,s) = & \arg\min_{p \in \{0,1\}} \mathbb{1}(p=0)\left(v(m-s) - v(m)\right) + \mathbb{1}(p=1)\,\kappa \\ = & \begin{cases} 0 & \text{if} \quad v(m-s) - v(m) \leq \kappa \quad \text{cash is used,} \\ 1 & \text{if} \quad v(m-s) - v(m) > \kappa, \quad \text{card is used.} \end{cases} \end{aligned} \tag{4}$$

Feasibility requires $p(m, s) = 1$ if $s > m$. We establish the following:

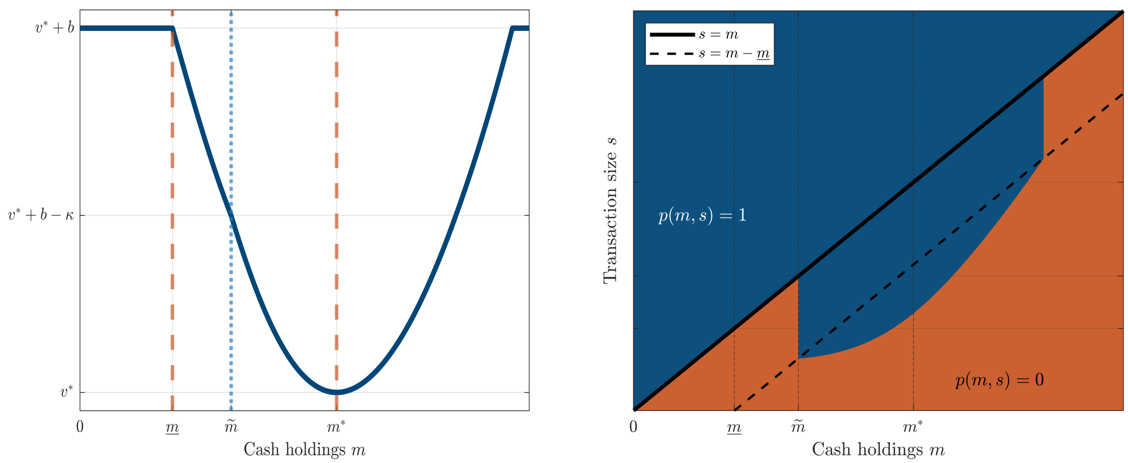
Lemma 1. *Let Assumption 1 hold. If* $p(m, s) = 0$*, then* $p(m, s') = 0$ *for any* $s' < s$*. If* $p(m, s) = 1$*, then* $p(m, s'') = 1$ *for any* $s'' > s$.

Proof. See Section B.1 of the Online Appendix. ■

unless the pdf f associated with F has mass points or "holes" in its support, the optimal policy is of the Ss type.

Figure 3: Optimal policy.

(A) Value function $v(m)$ and withdrawal policy. (B) Payment method policy function $p(m, s)$



Note: The right panel shows the value function $v(m)$ that solves problem (3). The right panel shows the policy function, with $p(m, s) = 1$ representing a card payment. The thick black line depicts the 45 degree line. The dashed black lines depicts the combination of levels of cash holdings m and purchase sizes s for which $m - s = \underline{m}$: above this line, if the agent pays cash she immediately withdraws afterwards. The parameters are those used in the calibration of the model for 2021-22 (see Section 4).

Lemma 1 establishes that payment method choices are monotone in the size of the transaction, for any level of cash holdings m. When facing a payment method decision, the agent compares the cost of paying with cash, i.e., the instantaneous change in the value of the problem $v(m - s) - v(m)$, with the cost of using cards κ. If v is weakly decreasing, the change in the value of the problem will always get more costly as s increases, for any m.

Note that any transaction s satisfying $m - s \in [0, \underline{m})$ is big enough that, if the agent decides to settle it using cash, she will need to visit an ATM immediately after. We label such purchases as *large*, as they trigger a cash withdrawal if settled in cash. The next lemma shows that there exists a critical threshold for cash holdings, $\tilde{m}$, such that large transactions are settled with the card only if $m > \tilde{m}$. This results illustrates the interactions that arise between the payment method choice and cash holdings:

Lemma 2. *Let Assumption 1 hold. Then, if* $0 < \kappa < b$*, there exists* $\widetilde{m} \in (\underline{m}, m^*)$ *satisfying*

$$v(\widetilde{m}) = v^* + b - \kappa, \tag{5}$$

such that whenever $m - s \in [0, \underline{m})$,

$$p(m,s) = \begin{cases} 0 & \textit{if} \quad m \in [\underline{m}, \widetilde{m}], \qquad \textit{(cash is used)} \\ 1 & \textit{if} \quad m \in (\widetilde{m}, m^*]. \qquad \textit{(card is used)} \end{cases} \tag{6}$$

Proof. See Section B.2 of the Online Appendix. ■

Lemma 2 states that if $0 < \kappa < b$, when facing a large purchase (i.e., such that $m - s \in [0, \underline{m})$), the agent adopts the following behavior. If the current cash balances are small, the difference between the cost of using the card ($v(m) + \kappa$) and the cost of using cash and withdrawing ($v^* + b$) is large, so that individuals prefer to use cash. The intuition is that when m is below $\widetilde{m}$ and a large purchase arises, it is not worth it to pay κ to keep cash holdings at the current level, which is far from the optimal one m^*. If a large purchase occurs when m is above $\widetilde{m}$, instead, the agent finds it optimal to pay κ to keep her cash holdings unchanged.

Combining the above Lemmas yields a Proposition that characterizes payment choices under the impulse control policy with trigger $\underline{m}$ and target m^*:

Proposition 1. *Let Assumption 1 hold. Then, for any* $0 < \phi \leq 1$*, we have that*

1. *for* $\kappa \leq 0$*, we have that* $p(m, s) = 1$ (card is used) *for all* $m \in [\underline{m}, m^*]$ *and for all* s*;*
2. *for* $0 < \kappa < b$*, there exists* $\widetilde{m} \in (\underline{m}, m^*)$ *such that*
   (a) *for any* $m \in [\underline{m}, \widetilde{m}]$*,* $p(m, s) = 0$ (cash is used) *for all* $s \leq m$*;*
   (b) *for any* $m \in [\widetilde{m}, m^*]$*, there exists a transaction size* $\underline{s}(m) \leq m - \underline{m}$*, satisfying*

$$v(m - \underline{s}(m)) = v(m) + \kappa, \tag{7}$$

   such that $p(m, s) = 0$ (use cash) *for all* $s < \underline{s}(m)$*, while* $p(m, s) = 1$ (use card) *for all* $s \geq \underline{s}(m)$*.*
3. *for* $\kappa \geq b$*, we have that* $p(m, s) = 0$ (use cash) *for all* $m \in [\underline{m}, m^*]$ *and* $s \leq m$*.*

Proof. See Section B.3 of the Online Appendix. ■

Proposition 1 highlights a number of features of payment choices. The payment policy for cases 1 and 3 is easily explained: when $k \leq 0$, using the card is cheaper than using cash, therefore the card option dominates cash. When $\kappa > b$, on the other hand, it is never optimal to use cards as using cash is more convenient, even when doing so leads to a shortfall and to the associated withdrawal; in this case, cards are a residual means of payment used only for forced transactions (when $s > m$). The payment policy for the case in which $0 < \kappa < b$ is depicted in Figure 3b. The main result is that using cards when cash on hand is sufficient to carry out the incoming transaction (i.e., below the 45 degree line) is optimal as long as the purchase size is larger than the threshold $\underline{s}(m)$, which varies with the level of cash holdings, m. In particular, when cash balances are sufficiently large ($m \geq \widetilde{m}$), the agent always uses cards for all purchases that would lead to a withdrawal if paid in cash (i.e., such that $m - s \leq \underline{m}$).[22] The reason is that when $\kappa < b$ the agent is willing to pay κ in order to avoid paying b, provided the current level of cash holdings is sufficiently close to the optimal one (i.e., it is larger than $\widetilde{m}$). As shown by the blue area below the dashed line in Figure 3b, it may also be optimal to use cards for some transactions that would not lead to an immediate withdrawal but would still push the agent too close to $\underline{m}$ (i.e., such that $m - s \in (\underline{m}, m - \underline{s}(m)]$), to avoid visiting a region of the state space where the probability of losing a purchase becomes non-negligible. Moreover, cash is always employed for sufficiently small transaction sizes, s (given that using cards entails a fixed cost). When cash balances are small ($m < \widetilde{m}$), cards are not used. In such cases, the agent is so far from the optimal level of cash holdings m^* that it is never worth to pay the fixed cost to keep the cash balances unchanged. Note that Proposition 1 holds true for any level of card acceptance $\phi \in (0, 1]$:[23] even though changes in ϕ affect the values of $\underline{m}, m^*$ and $\widetilde{m}$, the features of the payment policy described in the Proposition and portrayed in Figure 3b remain valid. Finally, we not that even when $\phi = 1$ the agent finds it optimal to use cash on some occasions, as long as $\kappa > 0$.

[22]This follows from (i) $\underline{s}(m) \leq m - \underline{m}$ and (ii) $p(m, s) = 1$ for all $s \geq \underline{s}(m)$, which imply that $p(m, s) = 1$ whenever $s \geq m - \underline{m}$, i.e., whenever $m - s \leq \underline{m}$.

[23]The proposition holds vacuously for $\phi = 0$ as the function p is not defined if cards are never accepted.

3.2 Model-implied observable statistics

We use the policy $(\underline{m}, m^*, p)$ to compute a set of moments that describe the cash management and payment method decisions of households, and that can be compared to observed statistics.

Cash management statistics. Average cash balances M in the economy can be obtained by computing the expected value of m under the invariant distribution of cash holdings $h(m)$. Notice that, due to the absence of a drift component, the density has a mass point at m^*. With a slight abuse of notation, we denote with $h(m)$ for $m \in [\underline{m}, m^*)$ the density of m, integrating to $1 - h(m^*)$, where $h(m^*) = \mathbb{P}\mathrm{r}(m = m^*)$. We show in Section B.5 of the Online Appendix that for any $m \in [\underline{m}, m^*)$ the invariant distribution satisfies the KFE

$$h(m) = \frac{\displaystyle\int_m^{m^*} h(m') f(m'-m) \left(1 - \phi p(m', m'-m)\right) dm' + h(m^*) f(m^* - m) \left(1 - \phi p(m^*, m^* - m)\right)}{\displaystyle F(m) - \int_0^m f(s) \phi p(m, s) ds}, \tag{8}$$

with boundary condition $\int_{\underline{m}}^{m^*} h(m) + h(m^*) = 1$. We solve (8) numerically and obtain the invariant distribution h; we can then trivially compute average cash holdings $M = \int_{\underline{m}}^{m^*} m h(m) dm + m^* h(m^*)$, as well as median cash holdings. We also want to compute the number of withdrawals per unit of time. To do that, we need to compute the function $\mathcal{T}(m)$, which gives the expected amount of time until the next withdrawal when cash balances are equal to m. We show in Section B.6 of the Online Appendix that $\mathcal{T}(m)$ obeys the functional equation

$$\mathcal{T}(m) = \frac{\displaystyle 1 + \lambda \int_0^{m - \underline{m}} f(s) \left(1 - \phi p(m, s)\right) \mathcal{T}(m - s) ds}{\displaystyle \lambda \left[F(m) - \int_0^m f(s) \phi p(m, s) ds \right]}. \tag{9}$$

After solving for $\mathcal{T}$, it is possible to obtain the average number of withdrawals performed by the agent per unit of time via the fundamental theorem of renewal theory $n = 1/\mathcal{T}(m^*)$, i.e., by exploiting the fact that the average number of withdrawals is the reciprocal of the length of a withdrawal cycle. It is also possible to compute the average cash on hand when a withdrawal takes place, denoted by $\underline{M}$, as well as the average size of withdrawals W (see Section B.7 of the Online Appendix for details).

Realized expenditure. Since some purchase opportunities are lost, the actual expenditure per unit of time e is weakly smaller than the intended expenditure $\widetilde{e} = \lambda \int_0^\infty sf(s)ds$. In particular, actual expenditure is given by

$$e = \lambda \cdot \left[\int_0^{\underline{m}} sf(s)ds + \int_{\underline{m}}^{\infty} sf(s) \left(1 - H(s)(1-\phi)\right) ds \right],$$

where the very last term is the probability of losing a purchase opportunity when cash balances are lower than z and the visited shop does not accept cards. The number of "realized" purchases is

$$\hat{\lambda} = \lambda \left(\int_{\underline{m}}^{m^*} h(m) \left(F(m) + (1 - F(m))\,\phi\right) dm + h(m^*) \left(F(m^*) + (1 - F(m^*))\,\phi\right) \right).$$

Payment choice statistics. The card share of expenditures γ is given by

$$\gamma = \frac{\lambda\phi \left(\int_{\underline{m}}^{m^*} h(m)\gamma(m)dm + h(m^*)\gamma(m^*) \right)}{e}, \tag{10}$$

where $\gamma(m) = \int_0^m sf(s)p(m,s)ds + \int_m^{+\infty} sf(s)ds$ is the share of expenditure paid with cards when having m units of cash on hand. We also want to capture how often cards are used conditional on having both options available, i.e., for *unforced* purchases. The card share of unforced expenditure $\widetilde{\gamma}$ is computed as

$$\widetilde{\gamma} = \frac{\lambda\phi \left(\int_{\underline{m}}^{m^*} h(m) \left(\int_0^m sf(s)p(m,s)ds \right) dm + h(m^*) \left(\int_0^{m^*} sf(s)p(m^*,s)ds \right) \right)}{\lambda\phi \left(\int_{\underline{m}}^{m^*} h(m) \left(\int_0^m sf(s)ds \right) dm + h(m^*) \left(\int_0^{m^*} sf(s)ds \right) \right)}. \tag{11}$$

It is also possible to compute the share of *purchases*, and not expenditure, settled using cards, both overall and when having both options available: we denote these two statistics by γ_n and $\widetilde{\gamma}_n$ (see Section B.7 of the Online Appendix for details).

3.3 Relationship with previous work

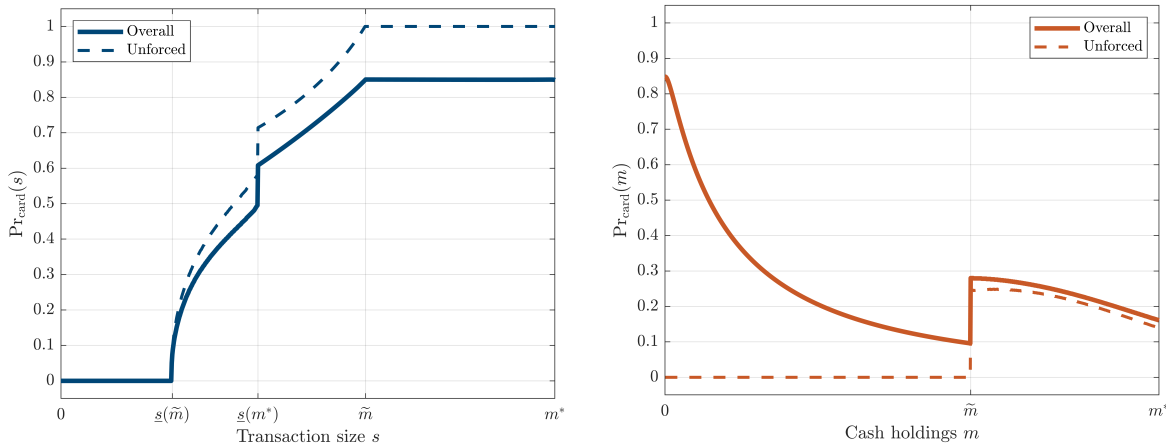
Theoretical models. Our model features a precautionary motive for holding cash which (if sufficiently strong) induces the agent to withdraw when she still has cash on hand ($\underline{m} > 0$). In particular, individuals want to hedge against an excessive frequency of card payments, which are costly to perform, and against the risk of missing a purchase. When m is close to zero, indeed, it is highly likely that the incoming transaction is too large to be settled with cash, which results in a forced card payment or, if the merchant does not accept cards, in a missed purchase. A similar feature appears in the model with uncertain lumpy expenditures by Alvarez and Lippi (2013), even though in their case the agent can finance lumpy transactions larger than her current cash balances by withdrawing *before* the purchase takes place, something that we do not allow here.

As for the payment method choice, our model can be seen as a generalization of those in Whitesell (1989) and Alvarez and Lippi (2017). In Whitesell (1989), households follow a transaction-size threshold policy, paying for large purchases (larger than $\underline{s}$) with cards and for small ones with cash. Here they adopt a similar behavior, even though the critical level of the transaction-size depends on the cash at hand, given by the function $\underline{s}(m)$. In Alvarez and Lippi (2017), households always use cash to settle transactions when they have enough. In their model, the expenditure stream is infinitesimal, hence we can compare their predictions with those we obtain for very small transactions. In our model too, when s is close to zero, it is optimal to use cash. This holds since using cash requires no immediate costs, and the value of the problem is only slightly affected by a tiny cash purchases, i.e., $m' = m - s \sim m$.

Empirical evidence. The optimal policies and the observable moments produced by our framework are broadly consistent with existing empirical evidence on payment choices and cash management, as well as with the new facts on payment behavior highlighted in Section 2. First, as shown in the left panel of Figure 4, the solution of our model implies that[24] the probability to use cards is increasing in the size of the transaction faced, as documented by

[24] After solving for the payment choice policy function $p(m, s)$ and for the invariant distribution $h(m)$, it is possible to compute the probability that cards are used as a function of s (the size of the transaction), m (the amount of cash on hand) and $m' = m - s$ (the amount of implied residual cash holdings). Details are provided in Section B.8 of the Online Appendix.

FIGURE 4: Probability of card usage as a function of s and m.



Note: In the left panel, we display the model-implied predicted probability of using cards as a function of the size of the incoming transaction s. In the right panel, we display the same probability as a function of the size of the incoming transaction s. Solid lines represent raw probabilities, while dashed ones represent the probability of using cards conditional on both payment methods being available. Parameters are those obtained from the calibration of the model for 2021-22 (see Section 4).

Klee (2008) and many others.[25] Second, consistently with the empirical literature showing that the probability to use cash increases as cash balances get larger (Stix (2004), Huynh, Schmidt-Dengler, and Stix (2014), Arango, Bouhdaoui, et al. (2014)), we show in the right panel of Figure 4 that for $m > \tilde{m}$ this pattern emerges in our model as well. A unique prediction of our model is that the intensity of cash usage (when both methods are available) is U-shaped in m. Not only the agent uses cash more often when she has a lot, but she does it often even when she has very little, as she knows that she will need to withdraw soon.[26] Overall, our payment choice rule closely resembles the patterns observed in the data, as can be seen by comparing the left panel of Figure 2, where we display the intensity of card usage as a function of m and s in the data, and Figure 3b, where we plot its model counterpart: qualitatively, the two plots look very similar. Third, our model also qualitatively reproduces the feature documented in the right panel of Figure 2, i.e., that the probability of using cards as a function of implied remaining cash holdings $m' = m - s$ (what would be left in the agent's

[25]As shown in the left panel of Figure 4, cash is always used for purchases of size smaller than $\underline{s}(\tilde{m})$. Cards are used more frequently as s rises, with a discontinuity at $\underline{s}(m^*)$ due to the distribution of cash holdings having a mass point at m^*. The probability of card usage reaches its peak for $s \geq \tilde{m}$, where it reaches ϕ (the card acceptance rate): for purchases this large, cards are always used when they are accepted.

[26]The right panel of Figure 4 shows that the probability of using cards for unforced purchases as a function of m peaks at $\tilde{m}$ and then falls. This happens because the closer m is to $\tilde{m}$, the steeper is the value function, and so the larger is the set of transactions that make the value of the problem increase by enough that card usage is warranted.

wallet if the incoming purchase is settled using cash) is flat for large enough m' and steeply rises as m' approaches zero.[27] Finally, we note that the model reproduces the empirical relationship between card acceptance and cash management: as ϕ falls, the precautionary motive for holding a cash buffer gets stronger, and the level of cash holdings $\underline{m}$ that triggers a withdrawal rises.[28]

4 Mapping the model to the data

In this Section, we calibrate the model mapping it to the data from payment diaries collected in the third wave of the ECB SPACE survey (2023-2024). Section 4.1 describes our calibration strategy in detail. Section 4.2 presents the results on the model's parametrization.

4.1 Calibration strategy

The set of parameters is given by $\{\rho, \phi, F, R, b, \kappa, u, \lambda\}$. We calibrate the model at the yearly frequency, using a mixture of external information for parameters that can be normalized or directly identified from the data and internal calibration (through minimum distance) for the remaining parameters.

Externally calibrated parameters. The discount rate is set to $\rho = 0.05$ to obtain an annual discount factor $\beta = 1/(1+\rho) \simeq 0.95$. The card acceptance rate ϕ is set equal to the share of merchants $\hat{\phi}$ who do not accept cards as a payment method. Given that imperfect acceptance may lead to some purchases being lost, we do not directly set the number of purchase opportunities λ equal to the observed number of purchases per year $\hat{\lambda}$ - on the contrary, we estimate λ internally, as explained below. We target a total *realized* expenditure of $e = \hat{\lambda}\int_0^{+\infty} sf(s)ds = \hat{\lambda}\mathbb{E}(s) = 365$, so that the average daily expenditure is equal to one. We calibrate the size distribution of payments from the data, using the following procedure. First, we assume that the distribution of transaction sizes F is lognormal, i.e., that $s \sim$

[27]See Figure D.1 in Section D of the Online Appendix, where we plot the model-implied function $\Pr_{\text{card}}(m')$.

[28]See Figure D.2 in Section D of the Online Appendix, where we show how the value function $v(m)$ and the withdrawal policy $(\underline{m}, m^*)$ change as ϕ rises from the levels observed in 2021-22 to that prevailing in 2023-24 (a 4pp increase).

TABLE 2: Calibration results and model fit.

Calibration results		**Model fit**	Data (2023-24)	Model
Externally calibrated parameters		*Targeted moments*		
Size distribution F, location μ_s	-1.95	Cash balances, M/e	1.34	1.30
Size distribution F, scale σ_s^2	2.63	N. cash withdrawals per year, n	96.40	96.68
Card acceptance rate ϕ	0.89	Card share of unforced expenditure $\widetilde{\gamma}$	0.46	0.46
		N. purchases per day $\hat{\lambda}/365$	1.90	1.91
Internally calibrated parameters (minimum distance)		*Untargeted moments*		
Withdrawal cost b (EUR)	0.003	Cash balances, M/e (median)	0.95	1.32
Card usage cost κ (EUR)	0.002	Cash balances, M/c	3.22	5.38
Lost purchase cost u (EUR)	0.976	Withdrawal size, W/M	1.18	0.70
Purchase oppurt. per day $\lambda/365$	1.92	Card share of expenditure γ	0.58	0.76

Note: This table contains our calibration results and information on the fit of the model to observed moments (SPACE data, wave 3, 2023-24). The parameter σ_s^2 is calibrated to match the coefficient of variation of purchase sizes $\widehat{\mathbb{CV}}_s$, and μ_s results from a normalization of total yearly expenditure to 365. Opportunity costs are normalized to $R = 10\%$. Cash balances are normalized by the overall daily expenditure e; we also display cash balances divided by daily *cash* expenditures c.

$LN(\mu_s, \sigma_s^2)$.[29] Our normalization of yearly expenditure delivers a parametric restriction on F, i.e., $\mathbb{E}(s) = \exp\left(\mu_s + \frac{\sigma_s^2}{2}\right) = 365/\hat{\lambda}$. Targeting the empirical coefficient of variation of transaction sizes $\widehat{\mathbb{CV}}_s$, we obtain another parametric restriction, i.e., $\sigma_s^2 = \log\left(\widehat{\mathbb{CV}}_s^2 + 1\right)$. The observed frequency of purchases and the coefficient of variation of payment sizes allow us to recover (μ_s, σ_s), and henceforth the cdf and the pdf f. The values of the externally calibrated parameters are displayed in Table 2.

Internally calibrated parameters. We estimate the remaining five parameters $\boldsymbol{\theta} = \{b, R, \kappa, \lambda, u\}$ in the following way.[30] We set $R = 10\%$, which we deem as a reasonable upper bound for the yearly opportunity cost of holding cash.[31] We then estimate the parameter vector $\widetilde{\boldsymbol{\theta}} = \{b, \kappa, u, \lambda\}$ in order to match four moments that summarize the cash management and payment behavior of the euro area households. The targeted moments are i) the average cash balances relative to daily expenditure M, ii) the number of withdrawals per year n, iii) the share of expenditure settled using a card when both options are available $\widetilde{\gamma}$, and iv) the number of realized purchases per year $\hat{\lambda}$.

[29]This is consistent with Figure A.7 in the Online Appendix, where we display the distribution of log payment sizes for all three surveys, which closely resemble a normal distribution.

[30]We note that the opportunity cost R is not identified separately from the other parameters. Let $\boldsymbol{\Theta}$ be the space of feasible structural parameter vectors $\boldsymbol{\theta} = \{b, R, \kappa, \lambda, u\}$, and let $\mu^{\boldsymbol{\theta}}$ be the set of model-implied observables. Consider $\boldsymbol{\theta}' = \{Sb, SR, S\kappa, \lambda, Su\}$, for some $S \in \mathbb{R}_{++}$. Then $\mu^{\boldsymbol{\theta}'} = \mu^{\boldsymbol{\theta}}$.

[31]In Knümann, Krüger, and Seitz (2024), R is estimated to be around 7% in Germany, the largest economy in the euro area. We could not find any comparable estimate of R for other euro area countries.

The average cash balance M informs us on the opportunity cost of holding cash R, as the agent holds lower balances when the opportunity cost is higher. The frequency of withdrawals n is informative about the utility cost u of missing a purchase: the higher is u, the more often the agent will visit ATMs to make sure that she does not hang around with little cash on hand. The share of expenditure (voluntarily) settled with cards helps us to pin down the card fee κ (recall that, as shown in Proposition 1, the share of expenditure voluntarily settled with cards approaches zero as $\kappa \to b$). We use $\hat{\lambda}$, the *observed* frequency of purchases, in order to recover λ, the frequency of purchase opportunities (see Section 3.2). We need to make sure that given the optimal policy and the size distribution of payments $F(s)$, the agent completes $\hat{\lambda}$ payments per year. We estimate $\widetilde{\boldsymbol{\theta}}$ via minimum distance,[32] i.e., for a given set of empirical moments $\widehat{\boldsymbol{\mu}} = \{\widehat{\mu}_i\}_{i=1}^4$, we choose $\widetilde{\boldsymbol{\theta}}^*$ such that $\widetilde{\boldsymbol{\theta}}^* = \arg\min_{\widetilde{\boldsymbol{\theta}}} \sum_{i=1}^4 \left(\frac{\mu_i^{\widetilde{\boldsymbol{\theta}}} - \widehat{\mu}_i}{\widehat{\mu}_i}\right)^2$, where $\{\mu_i^{\widetilde{\boldsymbol{\theta}}}\}_{i=1}^4$are model-implied moments.

4.2 Calibration results

In Table 2 we display calibrated values of the four structural parameters of the model $\{b, \kappa, u, \lambda\}$. We estimate a very small withdrawal cost b of 0.003 EUR. The fixed cost of using cards κ is even smaller than the cost of withdrawals b, as expected since households settle a sizeable share of unforced purchases with cards ($\widetilde{\gamma} = 0.46$); we estimate a value of κ/b around 60%. We also estimate that around 2% of purchase opportunities are missed due to a combination of insufficient cash holdings when the opportunity to buy arises and imperfect card acceptance. Finally, we estimate a utility cost stemming from each missed purchase opportunity of around 1 EUR.

In the second part of Table 2 we illustrate the fit of the calibrated model, both in terms of targeted moments and in terms of untargeted statistics. The model fits almost perfectly the four targeted moments. In terms of untargeted moments, we obtain model-implied values which are qualitatively in line with the data, even though the fit is not as good. For instance, we overestimate γ, the unconditional share of card purchases, by 18 percentage points. Since $c = (1 - \gamma)e$, this also implies that M/c is around 70% larger than its empirical counterpart.

[32]We numerically implement a global search method on a Sobol quasi-random low-discrepancy grid of candidate parameter vectors, paired with a local search algorithm around the candidates for a global minimum.

This shortcoming is likely due to the very simple nature of the model, which abstracts from many features of the data. For instance, in our model the probability of cards being accepted ϕ is independent of the size of the purchase s, while in reality cards are more often accepted for larger transactions than for small-sized ones (see Figure A.2 in the Online Appendix).

4.3 Welfare analysis

Let $\mathcal{C}$ denote the annual household's *cost of managing consumption transactions*. In a steady state this is

$$\mathcal{C} = RM + bn + \kappa\gamma_n\hat{\lambda} + u\left(\lambda - \hat{\lambda}\right), \tag{12}$$

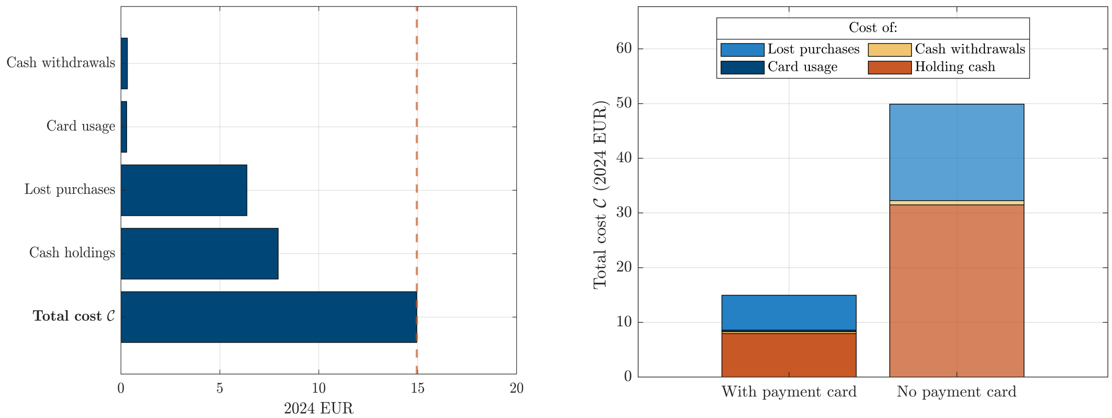
where $\gamma_n\hat{\lambda}$ is the number of card purchases and $(\lambda - \hat{\lambda})$ is the number of missed purchase opportunities. As (12) shows there are four sources of costs in the model, namely i) the *opportunity costs* of holding cash (RM), ii) the cost related to *cash withdrawals* (bn), iii) *card usage* costs ($\kappa\gamma_n\hat{\lambda}$), and iv) the cost stemming from *lost purchases*, $u\left(\lambda - \hat{\lambda}\right)$. Recall that we expressed cash holdings in terms of days of cash-expenditures, so that the cost $\mathcal{C}$ is also measured in days of consumption expenditures. We can thus express this value in 2024 euros by multiplying it by the average daily expenditure (approximately 61 euros). Figure 5a shows the estimated annual cost of managing consumption transactions, and how each of the four components contributes to the total cost: we estimate a cost of managing consumption transactions for the average household of approximately 15 euros per year, a remarkably low amount which suggests that the payment system faced by households imposes a relatively small burden on their budgets.

We note that the cost of transactions deliberately ignores that in order to pay for goods and services with either with cards or cash, households must hold liquid assets (typically overnight deposits), whose compensation is typically lower than that of alternative assets. We omit such costs because they are invariant with respect to the mix of cash vs card payment used, which is the core object of our exercise.

Heterogeneity. We use the richness of our data to estimate the model over different time periods and different demographic groups. In Figure D.3 in the Online Appendix we display the estimated cost of managing consumption transactions, and its component, for each survey

FIGURE 5: The cost of managing consumption transactions

(A) Total cost $\mathcal{C}$: a decomposition. (B) The benefit of holding a payment card.



Note: The left panel shows a decomposition of the total cost of managing consumption transactions $\mathcal{C}$ (expressed in 2024 euros) for the estimated model. The right panel compares the total cost of managing consumption transactions $\mathcal{C}$ for the estimated model with that obtained in an alternative scenario where we set $\phi = 0$, i.e., where the agent cannot use her payment card.

wave, from 2015-16 to 2023-24. Until 2019, the estimated total cost was around 20 euros per year, while it stabilised around 15 euros from 2021-22 onward. The difference is mostly due to households' holding less cash in the post-pandemic period. We also estimate the model on 2023-24 data for different age groups, levels of completed education, income brackets and by gender.[33] Given that these groups have very different overall daily expenditures, and that total costs rise with consumption, in Figure D.4 in the Online Appendix we display the estimated total annual cost as a fraction of daily expenditure for each subgroup. The main result is that each of these demographic subgroups faces a very similar cost, as a proportion of their expenditure.

5 Three counterfactual experiments

In this Section, we use the estimated model to run three counterfactual experiments. Section 5.1 quantifies the welfare benefit of holding a payment card. Section 5.2 describes a counterfactual scenario in which card acceptance is near-universal ($\phi = .99$). Section 5.3

[33]In Table 4 in the Online Appendix we display an extensive set of summary statistics for each wave of the survey. Table 6 in the Online Appendix presents our calibration for different time periods. Tables with summary statistics, estimated parameters and the model fit for all the other subsamples (by age, education and so on) are available upon request.

evaluates under which conditions the agent entirely abandons cash and a purely cashless economy emerges.

5.1 The benefit of holding a payment card

We use the estimated model to compute the benefit of holding a payment card. To do that, we solve the model again assuming that the agent does not own a payment card, but that cash is her only available instrument to settle transactions.[34] In Figure 5b we quantify the benefit of holding a payment card, by comparing the cost of managing consumption transaction $\mathcal{C}$ with its counterfactual for an agent who is not endowed with a payment card. Notice that R, b, κ and u are held fixed to their estimated values; therefore, any difference in costs we find is attributable to the different policies followed by the agent when she does not have access to a payment card. The results suggest that owning a payment card enables households to save around 70% on the total cost of managing consumption transactions. A household with no access to a payment card would spend 50 euros per year to manage consumption transactions (instead of 15): thus, the value of owning a payment card is around 35 euros per year.[35] The savings are mainly driven by the lower opportunity costs of holding cash (as having a payment card reduces the precautionary motive for keeping cash balances high) and by a lower disutility from lost purchases, while the decrease in withdrawal costs plays a negligible role.

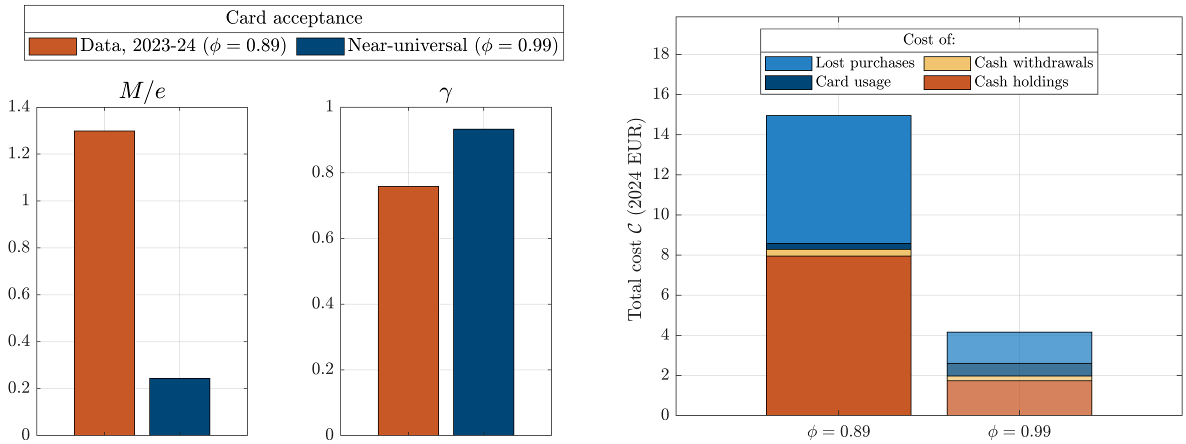
5.2 Near-universal card acceptance

We now analyze a counterfactual scenario in which 99% of all merchants accept payment cards, a scenario we refer to as "near-universal card acceptance". We start by comparing two key moments that summarize cash management and payment method choices by households. The left panel of Figure 6 shows both the model-implied average cash balance and the card share of expenditure in 2023-24 under the true card acceptance rate $\phi = 0.89$, and when we set $\phi = 0.99$. In the latter scenario the average cash holdings (relative to daily expenditures) decrease by around 110pp, from the current 130% of daily expenditure to about 20%. This

[34]We implement this by setting $\phi = 0$, i.e., by assuming that no merchants accept payment cards.

[35]This figure aligns with the cost of a bank account with a payment card in Italy, which was estimated at around 30-40 EUR/year in 2023 (Banca d'Italia, 2024).

FIGURE 6: Near-universal card acceptance: a counterfactual.



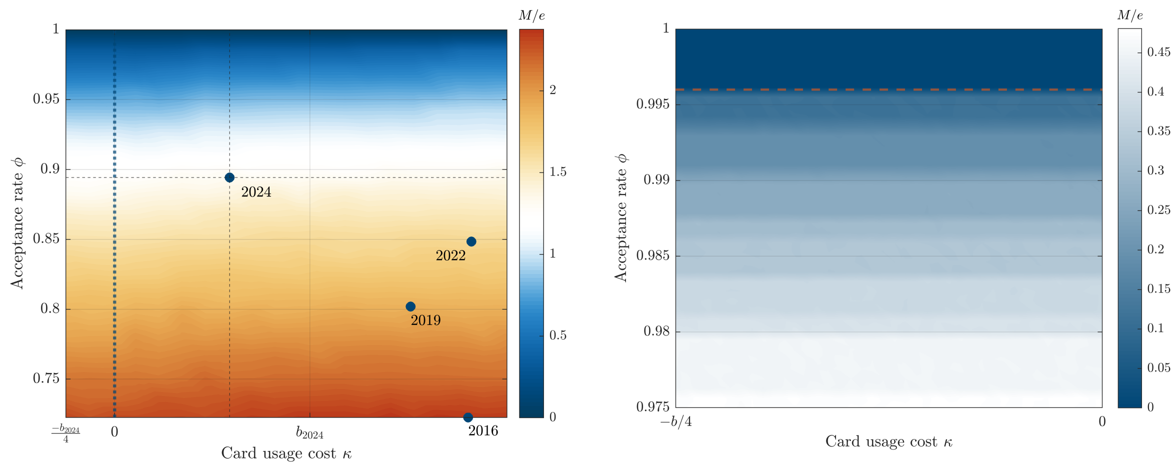
Note: The left panel compares counterfactual moments obtained by solving the estimated model for 2023-24 with $\phi = 0.99$ and their real-world counterparts under the true acceptance rate $\phi = \widehat{\phi} = 0.89$. Displayed moments are the average cash balances relative to daily expenditure M/e, and the share of expenditure settled using cards γ. The right panel shows the total cost of managing consumption transactions $\mathcal{C}$ (expressed in 2024 euros), both for the estimated model and for the alternative scenario with $\phi = 0.99$.

happens since with high card acceptance the agent resets her cash balances to a lower level m^* upon withdrawing, and the trigger cash level $\underline{m}$ decreases as well, since the insurance motive (associated with avoiding missed purchase opportunities) is now less relevant. The share of card expenditure by 17pp to about 93%, mostly due to an increase in the share of forced card transactions, as agents more frequently lack sufficient cash to complete their purchases. We find that the share of *unforced* card expenditures falls by around 10pp. This happens because, as acceptance rises, the precautionary motive to use cards when cash is an option (i.e., preserving a buffer-stock of cash balances) is weaker.

We then compute the welfare costs of imperfect acceptance of payment cards for households by comparing the estimated cost of managing consumption transactions $\mathcal{C}$ with its counterfactual value under near-universal card acceptance. The right panel of Figure 6 illustrates the welfare loss that imperfect acceptance generates with respect to the counterfactual world with $\phi = 0.99$: under near-universal acceptance the yearly cost of managing consumption transaction would be about 4 euros, almost 75% smaller than the baseline cost. The difference is mainly due to savings on the opportunity costs of holding cash and to the lower frequency of missed purchases.

Figure 7: Conditions for a no-cash policy.

(a) Full domain for (κ, ϕ) (b) Detail - northwest region.



Note: The left panel displays the model-implied moment M/e, i.e., average cash holdings normalized by daily expenditure for goods and services, in a set of economies with all parameters except κ and ϕ set to their estimated levels for 2023-24. We solve the model for a rectangular array of $\{\kappa, \phi\}$, with $\kappa \in [-b_{2024}/4, b]$ and $\phi \in [\hat{\phi}_{2015-16}, 1]$. The dashed blue line separates the right region, in which paying with cards is more expensive than using cash, from the left region, in which cards are a cheaper means of payment. The values of $\{\hat{\kappa}, \hat{\phi}\}$ estimated for 2015-16, 2019 and 2021-22 are overlaid to the plot. The dark blue area with $M/e = 0$ denotes the region in the space of (κ, ϕ) in which no-cash policies are optimal. The right panel zooms into the region where $\kappa \leq 0$ and $\phi \geq 0.975$ (bordered in orange at the northwest of the right panel). The colors are changed to ease visualization of the boundary (dashed orange line) of the set of parameters for which $M/e = 0$.

5.3 A cashless economy?

An interesting question is whether cash can be completely replaced by alternative payment technologies, and under which circumstances (see Shy (2023)). Our model allows us to investigate the conditions under which individuals stop holding cash and use their payment cards to settle all purchases. The cost of managing consumption transactions under a *cashless* policy is $\mathcal{C}_{\text{cashless}} = \lambda\left(\phi\kappa + (1-\phi)u\right)$, as individuals will perform no withdrawals nor will they bear any opportunity costs of holding cash: their only costs are that stemming from card fees when meeting a merchant that accepts cards, and from missed purchase opportunities otherwise. We estimate $\mathcal{C}_{\text{cashless}}$ to be approximately 75 euros per year, around 5 times larger than the cost of managing consumption transactions under the optimal mix of cash and cards, and about 25 euros higher than the cost of following a cash-only policy, quantified in Section 5.1.[36] Our model indicates that a complete ban on cash (as discussed by Rogoff

[36]Under a cashless policy, the average consumer would miss approximately 80 transactions per year (about 10% of total purchase opportunities) because of imperfect acceptance of cards. Multiplied by the estimated average

(2017) and Alvarez, Argente, et al. (2022)) would increase the cost of managing consumption transactions by 60 euros per year for the average consumer. We next perform the following exercise: using our parameter estimates we construct counterfactuals in which we vary the cost of using cards (κ) and the share of merchants that accept cards (ϕ). We solve the model for all values of ϕ higher than $\hat{\phi}_{2015-16}$, and for a vector of $\kappa \geq b_{2024}/4$. We also include some negative values of κ to take into account the possibility that card payments become cheaper than cash ones (recall that the cost of a cash payment is set to zero in our model): it is worth exploring the solution of the model for negative values of κ as in many surveys, a sizeable fraction of individuals indicate cards as their preferred payment method, as documented by van der Cruijsen, Hernandez, and Jonker (2017), among others, and as our data shows too.[37] For each $\{\kappa, \phi\}$-pair, we analyze under which combinations of these two parameters the transactions demand for cash by households becomes zero: we look at the model-implied average cash balances M/e, with $M/e = 0$ identifying a cashless economy. We display the results in Figure 7. The Figure shows that two conditions are necessary for the agent to completely abandon cash: universal or near-universal acceptance (ϕ above 99%), and cheap card payments (small κ), possibly even cheaper than cash ones (negative κ). A very high ϕ is needed for consumers to abandon cash since the estimated value of u, the cost of missing purchases, is quite large. Recall from Proposition 1 that cash is never used to pay for unforced purchases if $\kappa \leq 0$; therefore, the agent follows a no-cash policy whenever card acceptance is universal ($\phi = 1$) and $\kappa \leq 0$.[38] Notice that for $\kappa \leq 0$, M/e is insensitive to κ: the agent always pays with her card whenever she can, so M/e only depends on ϕ, i.e., on how often she runs into stores accepting cards. In the Figure, we also plot the values $\{\hat{\kappa}, \hat{\phi}\}$ for 2023-24, as well as those obtained by calibrating the model to match moments for 2015-16, 2019 and 2021-22: the estimates suggest that euro area households are getting closer to a no-cash policy over time, mainly because of increased merchant acceptance. With the currently estimated card usage

cost of missing a transaction (0.97 euros), the associated cost would amount to about 75 euros, accounting for more than 90% of total costs.

[37] SUCH and SPACE respondents were also asked about their payment method preferences through the question "If you were offered various payment methods in a shop, what would be your preference?" We display the responses for all survey years in Figure A.6 in the Online Appendix. A large fraction of households in the euro area reportedly prefers to pay using cards.

[38] While this is a sufficient condition for $M/e = 0$, we show in the right panel of Figure 7 that it is not a necessary condition, as $M/e = 0$ for all $\phi > 0.99$.

costs, though, even near-universal acceptance of cards by vendors would not be enough to produce a cashless economy.

6 Concluding remarks

This paper used granular data from payment diaries collected by the ECB to uncover new patterns in the payment choices of euro area households. We empirically show some limitations of the predictions of existing payment choice models. Transaction-level data illustrates that both the amount of cash on hand at the moment of a given purchase, and the size of the incoming purchase, are relevant predictors of decisions between cash and cards. Moreover, we show that a key determinant of card usage is a precautionary motive for holding cash: whenever the incoming purchase is large enough to deplete the consumer's cash balance, cards are more likely to be used. Finally, we document a relationship between card acceptance rates, i.e., the share of merchants willing to accept card payments, and cash management by households: in areas with lower card acceptance, individuals hold a precautionary buffer stock of cash, visiting ATMs when their wallets are still half-full.

We rationalize the above patterns through an inventory-theoretical model with uncertain lumpy expenditures of random size and a choice between cash and cards. The agent can decide whether to settle her purchases using a payment card (whenever she meets a merchant who accepts card payments), or with cash. Using cards involves the payment of a fixed cost, but keeps cash balances at a higher level. Whenever the cost of using cards is smaller than that of visiting ATMs, the agent sometimes optimally uses her card to pay even though she has sufficient cash on hand: in particular, whenever the cost of using cards is smaller than the increase in the value of the problem resulting from a cash payment, cards are employed. The optimal policy shares features of Whitesell (1989) (transaction-threshold type payment choices) and Alvarez and Lippi (2017) (choices depend on current cash holdings), rationalizing the micro-level evidence on payments of Section 2 in a unified framework.

We calibrate the model to replicate features of observed payments behavior in the euro area. The estimated cost of using cards is smaller than the cost of a cash withdrawal. We use the model to perform several counterfactual analyses, quantifying the costs of managing consumption transactions, the benefits of card ownership, the welfare costs of imperfect acceptance, and providing conditions under which a cashless economy might emerge.

There are three main caveats in the interpretation of our results, which stem from the simplicity of the model and that could be addressed in a more complete framework of analysis. First, in the model there are no exogenous inflows of cash: in order to obtain cash, the agent has to pay a fixed cost and she always resets cash balances to the optimal level. The data however show that households oftentimes receive part of their income as cash or obtain cash from friends, relatives and colleagues: including exogenous cash inflows in the model (adopting a framework a' la Miller and Orr (1966)) would incorporate this feature, which might be important in determining the resilience of cash. Second, our model does not allow the relative cost κ of using cards to depend on the transaction size s. There are, however, reasons why this assumption may be too restrictive. For instance, credit-card reward programs reimburse consumers for a portion of their card-based expenditures: in such cases, the effective cost of using cards decreases as s rises. A possible extension of our framework could allow for a more flexible card-usage cost, such as $\kappa(s) = \kappa_0 + \kappa_s s$, which could yield more nuanced implications for the substitutability between cash and cards. This extension may be particularly relevant when calibrating the model for an economy where reward programs are widespread, such as the United States. Third, our analysis is focused on the consumers' side of the problem, taking the share of stores that accept cards as given. This affects our computation of the welfare costs of imperfect card acceptance, as we neglect the potentially negative impact that full acceptance of payment cards could have on those merchants who are only willing to receive cash payments as of now.[39] Future work could model card acceptance choices as the outcome of a game between merchants, who may choose to accept cards, despite the associated fees, in order to attract more customers (Masters and Rodríguez-Reyes, 2005; Moracci, Sorbera, and Zamora-Peréz, 2026). This would allow for a joint evaluation of the margins that determine card acceptance rates, payment choices and cash management in equilibrium.

[39]It has been shown that card networks design fee structures which impose a greater share of transaction costs on merchants (Rochet and Tirole, 2014; Huynh, Nicholls, and Shcherbakov, 2022), discouraging some stores from accepting card payments.

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