EIEF WORKING PAPER SERIES

EINAUDI INSTITUTE FOR ECONOMICS AND FINANCE

EIEF Working Paper 24/15

December 2024

Cash or card? A structural model of payment choices

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December 4, 2024

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* emerge 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 employ 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.*

*We thank Fernando Alvarez and Russel Cooper for comments. Lippi acknowledges financial support from the ERC grant: 101054421-DCS.

1 Introduction

Advances in information technologies and digitization have changed 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-Peréz (2024)). In this paper, we present new evidence on means-of-payment choices in the euro area, drawn from surveys conducted by the European Central Bank. The transaction-level data shows that when households choose whether to pay using cash or cards, their behavior 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 that occurred on the same day, a behavior that contradicts the simple *threshold-rule* prediction by Whitesell (1989). Second, card payments are often chosen even when households have sufficient cash to carry out the transaction, contradicting *cash burns* policies that prescribe that cards should be used after running out of cash, as in Alvarez and Lippi (2017). Moreover, the data reveals a novel pattern in payment behavior: card usage is common when the size of the purchase is close to the level of cash on hand, i.e., when the residual money holdings in case of a cash payment are low. This evidence suggests the existence of a precautionary motive to hold a cash buffer: the household anticipates that cash may be needed for transactions where cards cannot be used.

We propose a dynamic inventory-theoretic 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 either using cash or a payment card, whose usage entails a fixed cost. When choosing how to pay, the agent trades off the benefit of using cash with the implicit rise in future costs induced by a reduction in cash balances. These future costs involve, among others, the welfare cost of missing a purchase opportunity when cards cannot be used. To avoid paying excessive card fees, as well as to insure against shopping trips in which cards are not accepted, the agent holds a precautionary stock of cash, visiting ATMs to withdraw cash well before her wallet is empty. 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 agent follows a transaction-size threshold policy– and of Alvarez and Lippi (2017) –namely, that cash is always employed to settle small value transactions. Moreover, 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 how much cash she has before the payment takes place.

The model has three key features. 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).[1] Second, we model the choice between cash versus card payments sequentially, so that the agent chooses whether to use cash or card, and whether to make a cash withdrawal, at each moment of time 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.[2] Third, we allow for imperfect acceptance of cards by merchants.[3] This assumption boosts the precautionary motive for holding a cash buffer. We document empirically that card acceptance is an important determinant of cash management practices.

We calibrate the model to match selected moments on cash management and payment choices for the euro area, computed from ECB diaries collected in 2021-2022. The calibrated structural parameters show that a card payment (per purchase) is more costly than a cash payment. This accounts for the fact that most small-sized purchases are done in cash. Still, the agent finds it optimal to use cards occasionally, as the cost of a card payment is lower than that of visiting the ATM to withdraw. An optimal mix of cash and card payments emerges as the solution to the problem of minimizing the cost of managing the agent's purchases.

[1]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).

[2]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.

[3]We do not model the merchants' choice, taking the fraction of stores in which cards are not accepted as given.

The estimated overall annual cost of managing transactions is small (around 9 euros for the average household). We analyze a counterfactual scenario where the agent can only use cash, and find that the estimated value of a payment card is around 17 euros per year (i.e. holding a card reduces the total costs of managing expenditures by around 65%). We estimate that the imperfect acceptance of cards by merchants generates a non-negligible cost for households: under near-universal acceptance of cards, the annual cost of managing cash and settling transactions would fall by 6 euros (-70% compared to the baseline). 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 85% to 99% does not eliminate cash usage; the share of cash expenditures (over total consumption) is reduced from the current 25% to about 10%. A purely cashless economy only emerges if *all* merchants accept cards, or if card payments become substantially cheaper than cash ones.

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.[4] A third potential determinant of payment choices by individuals are also supply-side factors such as limited acceptance of means of payments: 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

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

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 cash usage is optimal whenever the agent has enough (*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) considers a 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, within a dynamic cash management framework, and they estimate it to US payment 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 three 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 wave of the *Study on the payment attitudes of consumers in the euro area* (SPACE I from now on), carried out in 2019, and iii) the second wave of the same survey (SPACE II), that covers the 2021-22 period. Individuals participating in the survey are asked to record in a diary their payments on a given day.[5] 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*).[6] For each purchase, respondents are also asked if alternative payment methods were accepted at the point of sale. The level of cash holdings at the start of the diary day, as well as any other cash inflow or outflow 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), received it from others (as cash income, or by family and friends)

[5]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.

[6]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.3 displays how often each of these payment instruments is used within every wave.

Table 1: Summary statistics across the three waves.

	Time period								
	2015-16			2019			2021-22		
	Mean	Median	N_{obs}	Mean	Median	N_{obs}	Mean	Median	N_{obs}
Expenditure flow									
Daily expenditure (EUR)	33	12	64,632	46	13	41,155	64	29	39,766
N. daily transactions	1.8	2	64,632	1.7		41,155	1.9	2	39,766
Size of payment (EUR)	18	8	117,919	28	10	68,944	33	16	76,667
Households' cash management									
Cash holdings (EUR)	60	32	64,632	83	40	40,990	91	50	39,543
Pr(Withdraws cash)	0.11		64,632	0.13		41,155	0.22		39,343
Withdrawal size (EUR)	69	27	4,197	96	50	4,129	106	50	7,119
Sellers' acceptance of payment methods									
Card accepted	0.72		116,133	0.79		66,913	0.85		75,625
Cash accepted				0.97		80,029	0.94		83,376
Both methods accepted	0.72		116,133	0.76		66,913	0.78		75,625
Features of transactions									
Card possible	0.70		115,368	0.77		66,523	0.83		73,180
Cash possible	0.90		132,548	0.87		80,029	0.79		83,376
Unforced (both possible)	0.60		115,368	0.62		66,523	0.61		73,180
Households' payment method choices									
Pr(Card)	0.24		89,941	0.34		41,486	0.49		31,191
Pr(Card | Unforced)	0.26		52,037	0.31		23,841	0.43		17,528

Note: The daily expenditure and number of daily transactions are lower bounds for their true values as respondents could report at most eight purchases on the payment diary. The amount of cash holdings is that reported at the start of the diary day. Over the three waves, we observe a total of 264,594 transactions performed by 145,766 individuals. Statistics are computed from SUCH data (2015-16), and from waves I and II of SPACE (2019 and 2021-22, respectively).

or deposited it (either in cash reserves held at home or using an ATM). This information enables us to back up the level of cash holdings before each transaction takes place, for a large set of participants.[7] 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 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 2015-2022 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.

[7] See Appendix A.1 for the technical details on the data cleaning process and on the derivation of additional information from the original datasets.

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.[8] In Table 1, we display some summary statistics across the three waves. 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.[9] 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 been stable for the sample period around 60% 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%).

2.2 Patterns of payment choice: data vs models

Two 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.

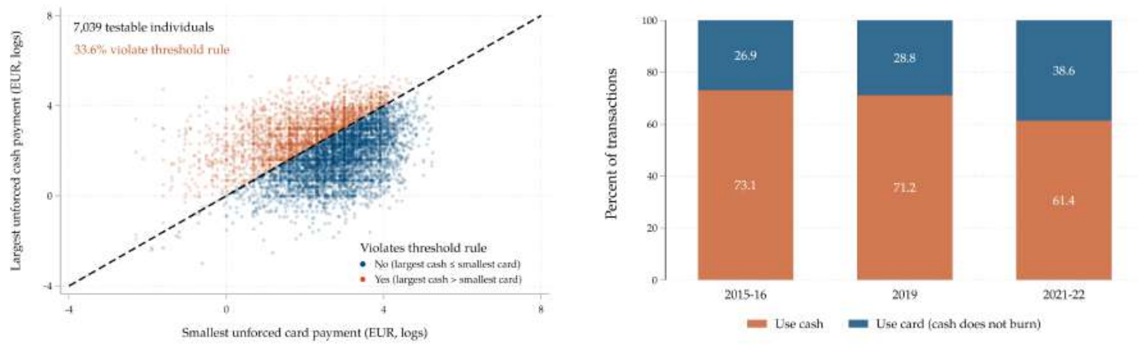
Transaction-size threshold policy. Some models emphasize the role played by the size of the transaction (which we denote by s) as a determinant of consumers' payment choices

[8] 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.

[9] 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 2021-22 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 7,039 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 and 2021-22).

(Prescott (1987), Whitesell (1989), Freeman and Kydland (2000)).[10] 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 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 37% of individuals explicitly violate the simple transaction-size threshold rule. This is contrast

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

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.

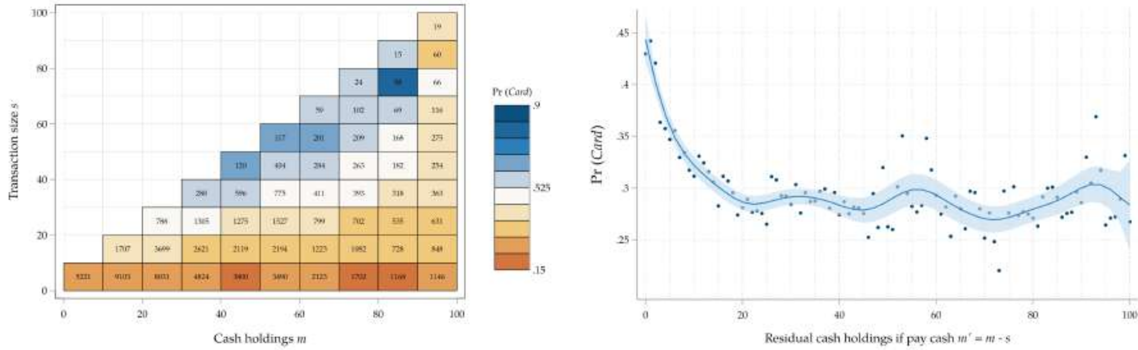
"Cash burns" policy. Other models of payment choices focus on the level of cash holdings at the moment in which the transaction takes place (which we denote by m). Motivated by empirical findings showing that consumers are more likely to use cash as a means of payment when cash balances are larger,[11] 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 simulation 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. Over all years, a substantial fraction (20 to 30%) of unforced transactions are paid by card: therefore, a theory in which cards are a residual means of payment, employed only when there are no other viable options, is at odds with empirical evidence.

2.3 More evidence on payment behavior

In this Section, we document a new stylized fact on payment choices. In the left panel of Figure 2, we display the relationship between payment method choices of individuals (cash vs cards), the amount of cash balances and the size of the purchase faced. 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

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

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. I 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 Figure A.5 and Figure A.6). 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 ($h = 5$) 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 and 2021-22).

available payment options.[12]

The Figure reveals that, for a given level of cash holdings m, the probability of using use 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 et al. (2012), Huynh, Schmidt-Dengler, and Stix (2014), Arango, Huynh, and Sabetti (2015), Bagnall et al. (2016)).[13] These facts provide strong evidence that both the transaction size s and the amount of cash holdings m affect individuals' payment choices.[14] The left panel of Figure 2 also illustrates that when the

[12]Notice that both 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.4, 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.

[13]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 find statistically significant relationships between the size of purchases/the level of cash balances and payment method choices (results are reported in Appendix A.2). On average, a 10 EUR increase in payment size s is associated with a 6pp (18%) increase in card usage probabilities, while a 10 EUR increase in cash holdings m is associated with a 3.88pp (12%) decrease in the probability of using cards.

[14]Further evidence that both m and s directly affect payment choices is provided by answers to SUCH survey

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 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.[15]

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 start by presenting the setup and the sequence problem faced by the agent. In Section 3.1 we present the Bellman equation and discuss the properties of 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 that 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 $\{N(t) : t \geq 0\}$ is the counter associated with a simple Poisson process with rate λ and $\{s_i : i \geq 1\}$ are i.i.d. random variables with continuous cdf $F(s)$ that satisfying $F(0) = 0$, where s is the size of purchases. We make this assumption to model a realistic expenditure flow, with purchase opportunities arising at random times and transactions having discrete sizes and

questionnaires. Consumers were asked the question "Which of the following influences your decision to pay with cash or card or other non-cash payment methods?". Their answers, that we report in Figure A.7, are consistent with our results: both the level of cash holdings and the size of the transaction are mentioned by more than 50% of respondents as drivers of their payment method decisions.

[15] 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 Appendix A.2 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 Appendix A.3.

following a non-degenerate distribution. We allow individuals to pay for their purchases using a payment card if they want to. Using cards entails a fixed cost κ, independent of the value of the purchase. We assume that cards are accepted in a fraction $\phi \in (0, 1)$ of stores.[16]

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 has a fixed cost $b > 0$. Cash balances must be higher than the size of the transaction in order to settle a purchase with cash ($m > s$). In the imperfect acceptance case ($\phi < 1$), when cash on hand is insufficient to carry out a purchase and the store visited 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.[17] The future is discounted at rate $\rho > 0$, and the agent faces the following problem

$$v(m) = \min_{\{w_{\tau_i}, \tau_i, \widehat{\tau}_i, \widetilde{\tau}_i\}_{i=0}^{\infty}} \mathbb{E} \left\{ \int_0^{+\infty} e^{-\rho t} Rm(t) dt + \sum_{i=0}^{\infty} \left(e^{-\rho \tau_i} b + e^{-\rho \widehat{\tau}_i} \kappa + e^{-\rho \widetilde{\tau}_i} u \right) \middle| m(0) = m \right\}$$
$$\text{subject to} \quad m(t) = m(0) + \sum_{\tau_i \le t} w_{\tau_i} - \sum_{i=0}^{N(t)} s_i \mathbb{1} \left(p_i = 0 \right), \tag{1}$$

where m is the level of cash balances, R is the opportunity cost of holding cash, b is the cost a withdrawal, κ is the cost of using cards, u is the cost of losing a purchase opportunity, w_τ is the size of the withdrawal occurred at time $t = \tau$ and $p_i = 0$ indicates that the ith purchase opportunity has been paid for using cash. We denote by $\{\tau_i, \widehat{\tau}_i, \widetilde{\tau}_i\}_{i \in \mathbb{N}}$, respectively, the *stopping times* at which withdrawals occur (τ_i), card payments are carried out ($\widehat{\tau}_i$), or purchase opportunities are lost ($\widetilde{\tau}_i$). As the constraint in (1) makes clear, the path of m, as well as the expected frequency of the three stopping times and expected discounted costs, are affected by the withdrawal and payment choices by individuals, which we describe next.

3.1 A characterization of the optimal payment policy

Consider an agent with cash balances m. We analyze withdrawal policies of the trigger-target form, characterized by a trigger value $\underline{m}$ and by a target value m^*. Define the target level of

[16] For simplicity, we assume that the share of merchants accepting cards is independent of the value of the good purchased.

[17] We assume that u is large enough that the agent will always choose to complete transactions if she has the option to do so.

cash balances as the value m^* that solves

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

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 her card and keeps her cash balances unchanged. When the store visited does not accept cards, the agent uses cash and the value function changes from $v(m)$ to $v(m-s)$.

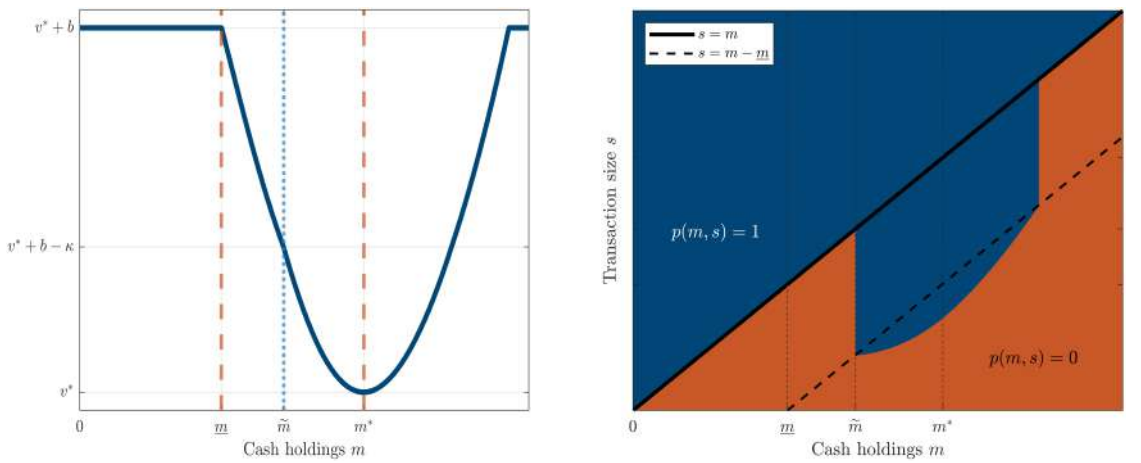
Next, we discuss the agent's optimal policy. This is given by two decision rules: a *withdrawal policy*, determining whether (and how much) to withdraw for any value of current cash holdings m, and a *payment policy*, which determines whether to use cash or cards to settle an expenditure of size s when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

Withdrawal policy. For a well-behaved transaction-size distribution F, the optimal withdrawal policy in our model 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 $m^* > \underline{m}$.[18] The

[18]The model setup is close to the stochastic, continuous-review inventory model (see Perera and Sethi (2023) for a complete review) 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). 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 unless the pdf f associated with F has "holes" in its support, the optimal policy is of

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).

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 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. Notice that in the example portrayed in Figure 3a, 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. When a trigger-target policy $0 < \underline{m} < m^*$ is used and v is weakly decreasing, it is possible to characterize the payment policy in detail. Let $p(m, s)$ denotes which payment method is employed when facing a purchase of size s and having m units of cash balances

the Ss type.

on hand, conditional on cards being accepted. For $s \leq m$, $p(m,s)$ is given by

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

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

Lemma 1. *Assume that $v(m)$ is weakly decreasing on $[0,m^*]$. 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 Appendix B.1. ■

Lemma 1 establishes that payment method choices are monotone in the size of the transaction faced, for any level of cash holdings m. Notice that whenever 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.

Notice that, for a given $m > \underline{m}$, any transaction s satisfying $m-s \in [0,\underline{m})$ is large enough that, if the agent decides to settle it using cash, she will need to visit an ATM immediately. We label such purchases as *large*, as they trigger a cash withdrawal if settled in cash. When facing a large purchase the agent uses her card whenever $v(m)+\kappa < v^*+b$, and she uses cash otherwise. With a weakly decreasing v, this implies that cards will be employed to settle large purchases when cash balances are high enough. The following Lemma establishes this feature of payment behavior.

Lemma 2. *Assume there exists $\underline{m} \geq 0$ such that $v(m) = v^*+b$ for any $m \leq \underline{m}$, and that $v(m)$ is continuous and weakly decreasing on $[0,m^*]$. Then,*

1. *for $\kappa \leq 0$, $p(m,s) = 1$ whenever $m-s \in [0,\underline{m})$;*

2. *for $0 < \kappa < b$, there exists $\widetilde{m} \in (\underline{m}, m^*)$ satisfying*

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

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

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

3. *for* $\kappa \geq b$*, then* $p(m,s) = 0$ *whenever* $m - s \in [0, \underline{m})$.

Proof. See Appendix B.2. ■

Lemma 2 states that, when facing a large purchase (i.e., such that $m - s \in [0, \underline{m})$), the agent adopts the following behavior if $0 < \kappa < b$. If current cash balances are small, the difference between the cost of using the card $v(m) + \kappa$ and the cost of using cash $v^* + b$ is large enough 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 higher than $\widetilde{m}$, instead, the agent finds it optimal to pay κ to keep her cash holdings unchanged.

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

Proposition 1. *Assume there exists* $\underline{m} \geq 0$ *such that* $v(m) = v^* + b$ *for any* $m \in [0, \underline{m})$*, and that* $v(m)$ *is strictly decreasing on* $[\underline{m}, m^*]$*. Then, for any* $0 < \phi \leq 1$

1. *for* $\kappa \leq 0$*, we have that* $p(m,s) = 1$ (card is used) *for all* $m \in [\underline{m}, m^*]$*;*

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 Appendix B.3. ■

Proposition 1 highlights a number of features of the model. The main result is that using cards when cash on hand is sufficient to carry out the incoming transaction is optimal when the purchase size is larger than some threshold $\underline{s}(m)$ which depends on the current level of cash holdings m. In particular, when she has sufficiently large cash balances ($m \geq \widetilde{m}$), the agent uses cards for the purchases that would lead to a withdrawal immediately after, if paid in cash (i.e., such that $m - s \leq \underline{m}$).[19] It is also optimal to use cards for some transactions that do not lead to an immediate withdrawal but 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, we show that for sufficiently small transaction sizes s, cash is always employed. When cash balances are small ($m < \widetilde{m}$), cards are not used. Notice that Proposition 1 holds true for any level of card acceptance $\phi \in (0,1]$:[20] even though changes in ϕ affect the values of $\underline{m}, m^*$ and $\widetilde{m}$, the shape of the payment policy $p(m,s)$ is the one described in the Proposition and portrayed in Figure 3b. Even when $\phi = 1$ the agent finds it optimal to use cash on some occasions, as long as $\kappa > 0$.

3.2 Model-implied observable statistics

We use the policy $(\overline{m}, m^*, p)$ 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 $h(m^*) = \mathbb{P}\text{r}(m = m^*)$. We show in Appendix B.4 that for any $m \in [\underline{m}, m^*)$

[19]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 $m - s \leq \underline{m}$.

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

the invariant distribution satisfies the KFE

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

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 $M = \int_{\underline{m}}^{m^*} mh(m)dm + m^*h(m^*)$, 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 Appendix B.5 that $t(m)$ obeys the functional equation

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

After solving for 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 Appendix B.6 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 $\gamma(m) = \int_0^m s f(s) p(m,s) ds + \int_m^{+\infty} s f(s) ds$ 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

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

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 Appendix B.6 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. 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. A similar feature is 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 not allowed here.

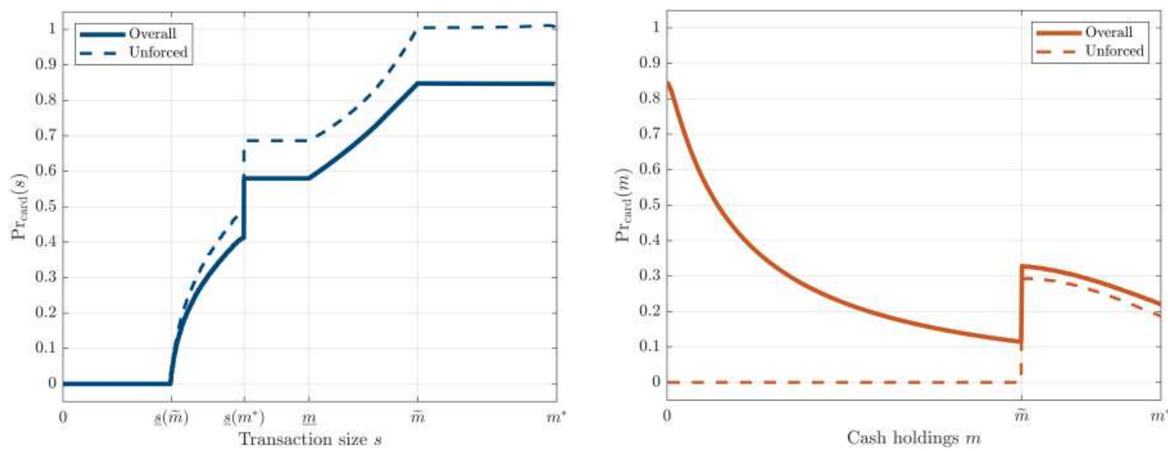
As for payment method choices, the optimal policy in our model can be seen as a generalization of those in Whitesell (1989) and Alvarez and Lippi (2017). In Whitesell (1989), households follow a transaction-size threshold policy, paying for large purchases (larger than $\underline{s}$) with cards and for small ones with cash. Here they adopt a similar behavior, even though transaction-size thresholds depend on the current level of cash holdings, i.e., they are a 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. Even in our model, when s is close to zero, it is always optimal to use cash. This holds since using cash require 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[21] the probability to use cards is increasing in the size of the transaction faced, as documented by Klee (2008) and many others. 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 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.[22] 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

[21] 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 Appendix B.7.

[22] The probability of using cards for unforced purchases as a function of m peaks at $\widetilde{m}$ and then falls. This happens because the closer m is to $\widetilde{m}$, 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.

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



Note: In Panel (A), we display the model-implied predicted probability of using cards as a function of the size of the incoming transaction s. In Panel (B), 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 discussed in Section 4.

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 wallet if the incoming purchase is settled using cash) is flat for large enough m' and steeply rises as m' approaches zero.[23] 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.[24]

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 second wave of the ECB SPACE survey (2021-2022). Section 4.1 describes our calibration strategy in detail. Section 4.2 presents the results on the model's parametrization.

[23]See Figure D.1 in Appendix D, where we plot the model-implied function $\Pr_{\text{card}}(m')$.
[24]See Figure D.2 in Appendix D, where we plot the value function $v(m)$ for different values of ϕ.

4.1 Calibration strategy

The set of parameters is given by $\{\rho, \phi, F, R, b, \kappa, \lambda, u\}$. 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 $e = \hat{\lambda} \int_0^{+\infty} s f(s) ds = \hat{\lambda}\mathbb{E}(s) = 365$, 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 $s \sim LN(\mu_s, \sigma_s^2)$.[25] 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. We set $b = 0.5 \times 10^{-4}$ (half a basis point) to ensure that estimated R takes values in the same order of magnitude as the yearly interest rate.[26] We then estimate the parameter vector $\widetilde{\boldsymbol{\theta}} = \{R, \kappa, \lambda, u\}$ in order to match four moments that summarize the cash management and payment behavior of the euro area households. The targeted moments are

[25] This is consistent with Figure A.10, where we display the distribution of log payment sizes for all three surveys, which closely resemble a normal distribution.

[26] We note that the fixed cost of withdrawals b 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 (for given externally calibrated parameters). Let $\boldsymbol{\theta}' = \{b', R', \kappa', \lambda', u'\}$ and $\boldsymbol{\theta}'' = \{\alpha b', \alpha R', \alpha\kappa', \lambda', \alpha u'\}$, for some $\alpha \in \mathbb{R}_{++}$. Then, $\mu^{\boldsymbol{\theta}'} = \mu^{\boldsymbol{\theta}''}$.

TABLE 2: Calibration results and model fit.

Calibration results		**Model fit**	Data (2021-22)	Model
Externally calibrated parameters		*Targeted moments*		
Size distribution F, location μ_s	-1.717	Cash balances, M/e	1.13	1.15
Size distribution F, scale σ_s^2	2.121	N. cash withdrawals per year, n	93.15	94.80
Card acceptance rate ϕ	0.845	Card share of unforced expenditure $\widetilde{\gamma}$	0.44	0.43
		N. purchases per day $\hat{\lambda}/365$	1.93	1.92
Internally calibrated parameters (minimum distance)		*Untargeted moments*		
Opportunity cost R	0.063	Cash balances, M/e (median)	0.75	1.15
Card usage cost κ/b	0.601	Cash balances, M/c	2.66	4.62
Purchase oppurt. per day $\lambda/365$	1.928	Cash at withdrawals, $\underline{M}/M$	0.84	0.41
Lost purchase cost u/b	80.341	Withdrawal size, W/M	1.29	0.83
		Card share of expenditure γ	0.57	0.75
		Share purchases lost		0.02

Note: This table contains our calibration results and information on the fit of the model to observed moments (SPACE data, wave 2, 2021-22). 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. Fixed withdrawal costs are normalized to $b = 0.5 \times 10^{-4}$. The cost κ of card usage and the cost u of lost purchases are reported as a fraction of b. The number of purchase opportunities per year λ is rescaled at the daily level. Cash balances are normalized by the overall daily expenditure e; we also display cash balances divided by daily *cash* expenditures c.

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 $\hat{\lambda}$.

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,[27] 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.

[27]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.

4.2 Calibration results

In Table 2 we display calibrated values of the four structural parameters of the model $\{R, \kappa, \lambda, u\}$. We estimate an opportunity cost of holding cash R of around 6% per year. The fixed cost of using cards κ is smaller than the cost of withdrawals b, as expected since households settle a sizeable share of unforced purchases with cards ($\widetilde{\gamma} = 0.44$); 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 around 80 times larger than the fixed cost of a withdrawal.

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 values for most statistics which are close to the data. The exception is $\underline{M}/M$, the average level of cash on hand when a withdrawal takes place relative to average cash balances, which we underestimate. The precautionary motive induced by imperfect acceptance and by the cost of using cards is enough to generate a positive $\underline{M}/M$, but the fitted value is around 50% smaller than its empirical counterpart.

4.3 Welfare analysis

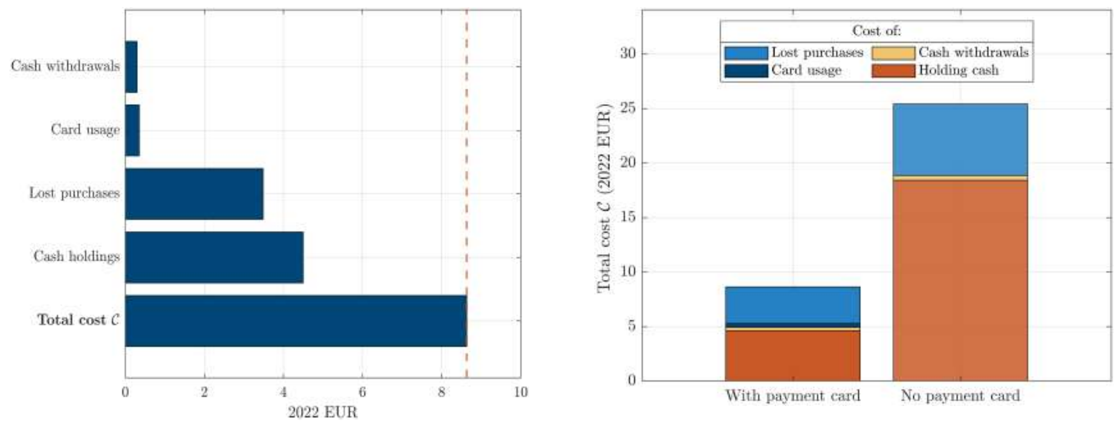
Let $\mathcal{C}$ denote the *cost of managing consumption transactions* over a year in steady state, given by

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

where $\gamma_n\hat{\lambda}$ is the number of card purchases and $(\lambda - \hat{\lambda})$ is the number of missed purchase opportunities. As (12) makes clear, 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 total cost $\mathcal{C}$ is also measured in days of consumption expenditures. We can thus express this value in 2022 euros

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 2022 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.

by multiplying it by the average daily expenditure (approximately 64 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 total cost of managing consumption transactions for a household of approximately 8.6 euros per year.

5 Three counterfactual experiments

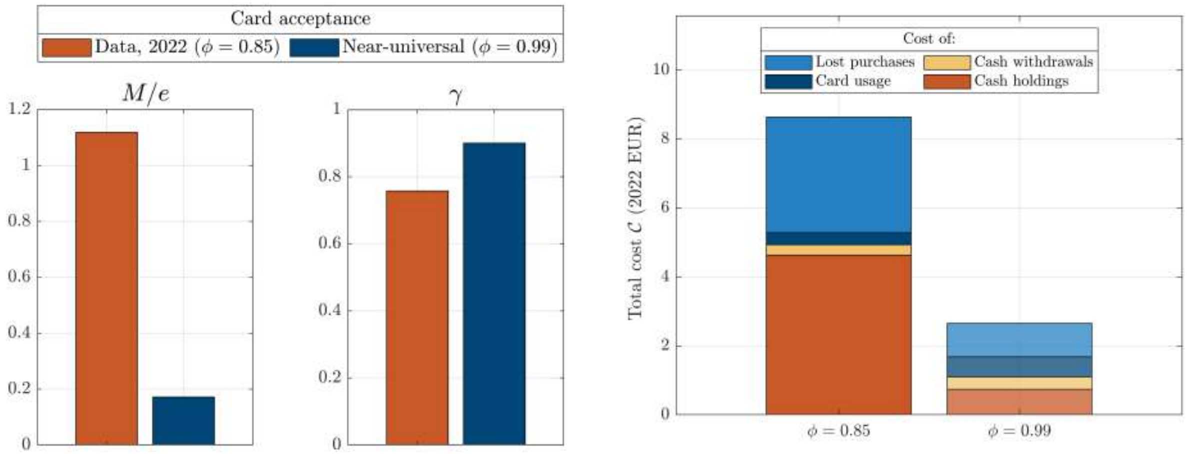
In this Section, we use the estimated model to run three counterfactual experiments. Section 5.1 quantifies the welfare benefit of holding a payment card. Section 5.2 describes a counterfactual scenario in which card acceptance is near-universal ($\phi = .99$). Section 5.3 evaluates under which conditions 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.[28] In Figure 5b we quantify the benefit of

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

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



Note: The left panel compares counterfactual moments obtained by solving the estimated model for 2021-22 with $\phi = 0.99$ and their real-world counterparts under the true acceptance rate $\phi = \widehat{\phi} = 0.85$. 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 2022 euros), both for the estimated model and for the alternative scenario with $\phi = 0.99$.

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 65% on the total cost of managing consumption transactions. A household with no access to a payment card would spend 25 euros per year to manage consumption transactions (instead of 8): the value of owning a payment card is around 17 euros per year. 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

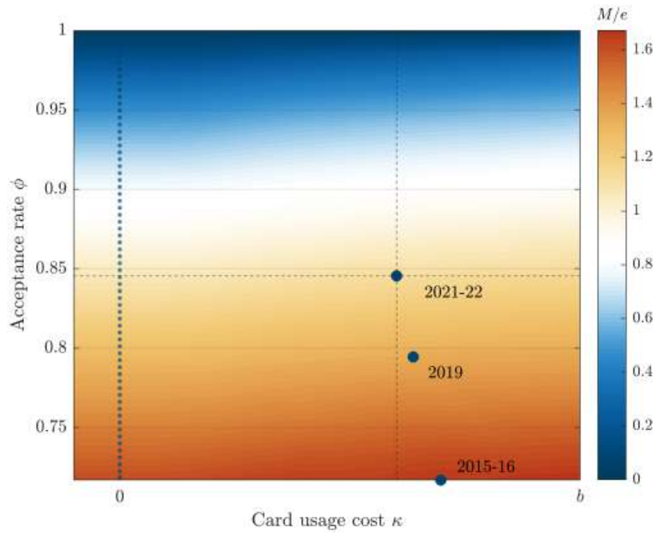
We now analyze a counterfactual scenario in which 99% of all merchants accept payment cards. We start by comparing two key moments that summarize cash management and payment method choices by households with their values under "near-universal card acceptance". The left panel of Figure 6 shows both the average cash balance and the card share of expenditure in 2021-22, and their values implied by the estimated model when we set $\phi = 0.99$. With near-universal card acceptance, the average cash holdings (relative to daily expenditures) decrease by around 95pp, from the current 115% of daily expenditure to less than 20%. This 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 card share of expenditure rises to approximately 90%, compared to 75% under the true acceptance rate in 2021-22.

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 $\phi = .99$: under near-universal acceptance the yearly cost of managing consumption transaction would be about 6 euros, about 70% 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.

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. As we highlighted in Section 3.1, the expected discounted cost of following a *no-cash* policy is $\overline{v} = \frac{\lambda(\phi\kappa+(1-\phi)u)}{\rho}$, as individuals will perform no withdrawals nor will they pay 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 now perform the following exercise: we take our parameter estimates and we construct counterfactuals in which we vary two key objects, 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 all $\kappa \in [-b/10, b]$. We also 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

FIGURE 7: Conditions for a no-cash policy.



Note: The graph 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 2021-22. We solve the model for a rectangular array of $\{\kappa, \phi\}$, with $\kappa \in [-b/10, b]$ and $\phi \in [\hat{\phi}_{2015-16}, 1]$. The dashed blue line separate 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.

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.[29] 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 things are necessary for the agent to completely abandon cash: universal or near-universal acceptance (ϕ close to or above 95%), and very cheap card payments (small κ), possibly even cheaper than cash ones. 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 $\kappa \leq 0$. Notice that for $\kappa \leq 0$, M/e is insensitive to

[29] 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.9. A large fraction of households in the euro area reportedly prefers to pay using cards.

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 2021-22, as well as those obtained by calibrating the model to match moments for 2015-16 and 2019:[30] 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 costs, though, even near-universal acceptance of cards by vendors would not be enough to produce a cashless economy.

6 Conclusion

In this paper, we use granular data from the ECB payment diaries to uncover new patterns in the payment choices of households. We empirically show some limitations of the predictions of existing models concerning payment method choices. 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 (relative to cash balances) to deplete consumers' wallets almost completely, 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 use her card to pay even though she has sufficient cash on hand: in particular, whenever the cost of using cards is smaller

[30] Detailed results are available upon request.

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, we assume that cash is universally accepted, while recent data reveal that many stores are not willing anymore to accept cash payments. Future work on this topic should investigate which role can the imperfect acceptance of cash payments play in the transition to a cashless economy by explicitly introducing this friction into structural models. Third, in our analysis of the welfare costs of imperfect card acceptance, we only focus on the costs sustained by buyers, neglecting the potentially negative impact that full acceptance of payment cards could have on merchants who are only willing to receive cash payments as of now. A deeper analysis would need to take into account such costs by modeling the acceptance choice of sellers as well, and evaluating which margins determine equilibrium card acceptance rates.

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A Empirical appendix

A.1 SUCH and SPACE data: additional information and data cleaning

The raw version of the data made available by the ECB has a major shortcoming: participants are not asked to report the level of their cash holdings in the moments in which they perform transactions. At a first glance, this lack of information may seem no big deal: given that in reported their money balances at the start of the day, using the data on withdrawals and payments cash holdings should be straightforward to pin down at each point in time. Two issues arise nonetheless: first, a fraction of agents failed to report the timing of cash adjustments performed (for SPACE data, respondents were not asked); second, even though they reported how much cash they "put aside" in total during the day, they were not asked about the timing and number of cash deposits.

To minimize the loss of data related to these shortcomings, we adopt the following strategy. Concerning the first problem, we can recover the timing of cash replenishments for a share of the agents which did not report it: using the fact that we can observe which payment method they employed in each transaction, we are able to pin down the timing of withdrawals in all situations in which an withdrawal is needed to explain a purchase (i.e., in which an agent purchased in cash a good/service with a price higher than her *unadjusted* cash holdings). The individuals for which the timing of replenishments couldn't be pinned down exactly were not excluded from the data, but the transactions for which the level of cash holdings was uncertain were dropped. The second issue can also be tackled exploiting the fact that agents reported their cash holdings at the end of the day. For all the agents for which we are able to track cash holdings, we can compute our predicted cash balances at the end of the day *assuming there were no deposits*. If the two figures differ, then an unreported deposit or replenishment must have taken place during the day, and we are therefore not sure that cash on end at time of each transaction is corresponding to the actual one. These observations were excluded as well, and so were the ones for which computed cash balances were negative at some point.

The final sample we use for the analysis contains information on 263,530 transactions carried out by 145,553 individuals. For a subsample of SUCH respondents and for all SPACE participants, we have access to a larger amount of information, since they also filled in a survey questionnaire.

A key aspect of the data is that it allows, for a large share of transactions, to perfectly observe the payment choice set of individuals, i.e., if they could use cash, cashless methods or both. First, tracking cash holdings at the moment of payments makes it possible to compare them with the associated transaction size and thereby to establish (for all payments) if it was possible to carry out the transaction using cash, given that we also have information on whether cash was accepted at the store or not.[31] Formally, let m_{it} be cash holdings of individual i at time t and s_{it} be the transaction size she faces. Our dummy for the possibility to use cash $CashPossible_{it}$ is constructed by

$$CashPossible_{it} = \begin{cases} 1 & \text{if} \quad s_{it} \leq m_{it} \vee CashAccepted_{it} = 1 \\ 0 & \text{if} \quad s_{it} > m_{it} \wedge CashAccepted_{it} = 0 \end{cases}$$

Second, combining information on card acceptance by merchants provided by respondents, payment methods employed and questionnaire answers, it has been possible to determine for a large share of payments if card payments were really an option for agents. There are two situations in which we are sure that card payments were an available option. The first situation, of course, is the one in which respondents *did* report to have used their cards to settle the transaction. The second situation is identified when two conditions are met: first, card payments must be accepted as a way to carry out the transaction (a condition I could check for all payments); second, the agent must have access to a payment card[32] (which I could check for a large fraction of payments[33]). Formally, let $CardOwner_i$ be a dummy

[31] The latter information is available only in SPACE data. For SUCH, we assume that cash was always accepted by merchants, which is a reasonable assumption given that in the first wave of SPACE the percentage of merchants accepting cash (surely smaller than that prevailing when SUCH was rolled out) was 97%.

[32] Since I don't know exactly which payment methods are accepted at any given transaction, but I just know if any cashless payments are accepted, I assume that an agent *could* have made a cashless payment at a store in which cashless instruments are accepted *if and only if* he/she has access either to a debit or to a credit card or both. The reason behind this is that credit and debit cards are always accepted in stores that accept some cashless payment method, while (for instance) cheques are not. Thereby, saying that an agent which has access to cheques (or credit transfers) could have paid cashless at a store in which cashless methods are accepted would be very risky, while for agents that own either a credit or a debit card it seems reasonably safe.

[33] This are all the payments made by respondents to the questionnaire, for whom we have detailed information concerning access to cashless instruments, plus all the payments made by agents which performed at least a card payment.

equal to one if individual i owns a payment card (debit or credit) and to zero if she doesn't. Let $CashlessOwner_i$ be equal to one if individual i has access to at least a cashless payment method and equal to zero otherwise. Let $CashlessOwner_{it}$ be a dummy equal to one if for the payment faced at time t by individual i cashless payments are accepted. Let $PayCash_{it}$ be a dummy equal to one if the payment method used by i at time t was effectively cash, and equal to zero otherwise. Our dummy for the possibility to use cashless methods $CashlessPossible_{it}$ is constructed in the following way.

$$CashlessPossible_{it} = \begin{cases} 1 & \text{if} \quad Cash_{it} = 0 \vee \langle CardOwner_i = 1 \wedge CashlessAccepted_{it} = 1 \rangle, \\ 0 & \text{if} \quad CashlessAccepted_{it} = 0 \vee CashlessOwner_i = 0, \\ \cdot & \quad\quad \text{otherwise,} \end{cases}$$

where $\cdot$ represent a missing value. For these transactions I can exactly pin down the payment choice set of individuals, and I'm thereby able to distinguish between *forced* (only cash or only payment card available) and *unforced* (both available) payment choices. Formally, let $Unforced_{it}$ be a dummy variable denoting *unforced* payments, i.e., a dummy equal to one when both payment options (cash and cashless) were available for individual i at time t and to zero when only one was available, which is constructed in the following way.

$$Unforced_{it} = \begin{cases} 1 & \text{if} \quad CashPossible_{it} = 1 \wedge CashlessPossible_{it} = 1 \\ 0 & \text{if} \quad CashPossible_{it} = 0 \vee CashlessPossible_{it} = 0 \\ \cdot & \text{if} \quad CashlessPossible_{it} = \cdot \end{cases}$$

A.2 Payment choices: regression analysis

In this Subsection, we test if the descriptive findings of Section 2 are robust to a more sophisticate analysis. In principle, it could be that patterns emerging in Figure 2 are entirely due to selection: for instance, it might be that households who generally prefer to use cards have on average lower cash holdings, or that they buy more valuable goods. As our data contains multiple transactions per individual, we can rule out these potential issues by relying on fixed effects models. In particular, we want to assess whether i) higher s increases the probability of a cashless payment, ii) higher m decreases the probability of a cashless payment; iii) the effects of a rise in s is stronger when m is smaller and viceversa, as m'

Table 3: Regression evidence on the joint importance of m and s.

Unit: EUR 100	Dependent variable: $PayCard_{it}$							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cash holdings m	-0.12***	-0.11***	-0.042***	-0.060***	-0.060***	-0.054***	-0.0079**	-0.026***
	(0.0017)	(0.0018)	(0.0024)	(0.0028)	(0.0022)	(0.0022)	(0.0029)	(0.0032)
Payment size s	0.68***	0.60***	0.40***	0.45***	0.90***	0.79***	0.64***	0.72***
	(0.0053)	(0.0055)	(0.0100)	(0.010)	(0.0084)	(0.0086)	(0.016)	(0.017)
Cash holdings m $\times$ Payment size s					-0.25***	-0.21***	-0.17***	-0.18***
					(0.0074)	(0.0071)	(0.0089)	(0.0095)
Observations	159359	144525	83412	91995	159359	144525	83412	91995
Unforced			✓	✓			✓	✓
Controls		✓	✓			✓	✓	
Random effects				✓				✓
Robust SEs	✓	✓	✓	✓	✓	✓	✓	✓

Note: Controls include demographic characteristics of individuals (region, country, year of the survey, sex, age group, income, education), as well as available characteristic of payments (type of store where the transaction was carried out, transaction number within diary day). Columns (2-3) and (6-7) include controls such as sex, age group, education and income of respondents. Columns (3-4) and (7-8) only take into account unforced transactions, i.e., transactions where both payments methods were available for the respondent. Columns (4) and (8) include individual-level random effects. Heteroskedasticity-robust standard errors are reported.

matters for choices. [34] We estimate linear probability models of the form

$$PayCard_{it} = \beta_0 + \beta_s s_{it} + \beta_m m_{it} + \beta_{sm}\left(s_{it} \times m_{it}\right) + \lambda' \mathbf{X}_{it} + \alpha_i + \varepsilon_{it}, \tag{13}$$

where $PayCard_{it} = 1$ $(= 0)$ if individual i settles her tth transaction using cashless methods (cash), $\mathbf{X}_{it}$ denote transaction-specific characteristics and α_i denote individual-level fixed effects.

The results are displayed in Table 3. Models (1) to (3) are intended to test whether card usage probabilities are increasing in the size of the transaction s and decreasing in the amount of cash holdings m. Our preferred specification (column (3), where we focus

[34] To test if choices are affected by m', we can estimate whether the effect of s is different according to the level of m. If s only affects choices through perceived cost/benefits of using cash instead of cards (for instance, because there are proportional fees, or because agents dislike paying small sums using their card as they perceive that merchants prefer them to pay cash), the effect of s should be independent of m, as long as $s \leq m$. At the same time, if agents care about the level of m because they want to get rid of cash they have, the effect of m shouldn't depend on s, as long as $s \leq m$. The presence of a significant interaction term points towards the existence of a more complex relationship between s, m and choices, which would be consistent with the story suggested by the previous two Figures. If households don't want to run out of cash, higher s increases the probability of cashless payments, but the effect of s is smaller as m grows. At the same time, higher m decreases the probability of a cashless payment, and it decreases it more when s is larger (as one abandons the region when $m - s \simeq 0$).

on unconstrained payments and include transaction-specific controls) reveals that a EUR 10 increase in cash holdings m is associated with 3.8pp decrease in the probability of paying by card. The opposite is true for the transaction size: a 10 EUR increase in s is associated with a 6pp rise in the probability of card usage. Models (4) to (6) are instead meant to test the whether choices are really driven by $m' = m - s$. In order to do so, we can estimate whether the effect of m changes[35] depending on the level of s. In particular, if agents really want to avoid running out of cash, thereby increasingly relying on cards as $m' \to 0$, we should find a negative coefficient on the interaction between cash holdings and payment size[36]. The estimated coefficient is indeed negative and statistically significant, corroborating our descriptive analysis. In particular, we find that the probability of a card payment decreases by 3.2pp for a EUR 10 increase when the payment size $s$is close to zero, but the marginal impact of cash holdings becomes stronger as the transaction size rises: for instance, for a EUR 50 payment, having 10 more euros on hand is associated with an extra probability of paying with cards of 4pp. Similarly, notice that the effect of payment size decreases as m rises, and even turns negative for sufficiently high cash holdings. Notice that this is consistent with optimal cash holdings being finite: if agents optimally want to hold a quantity of cash m^*, for $m > m^*$ they will increasingly use cash as s increases, as when cash holdings are very high, large payments can be exploited to bring cash holdings closer to their optimal value.

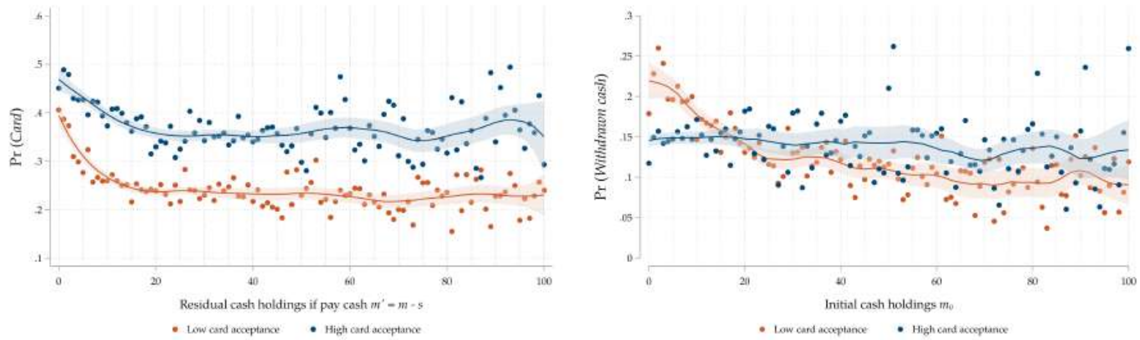
A.3 The role of imperfect card acceptance

The evidence of Section 2 shows that households prefer to avoid having too little cash and therefore use cards when doing otherwise would result in a near depletion of their cash balances. This suggests the existence of a precautionary motive to hold a buffer stock of cash. A possible driver of such precautionary motive is avoiding situations in which cash balances are too low to carry out a transaction, especially if there is a significant risk that cards are

[35]If s only affects choices through perceived cost/benefits of using cash instead of cards (for instance, because there are proportional fees, or because agents dislike paying small sums using their card as they perceive that merchants prefer them to pay cash), the effect of s should be independent of m, as long as $s \leq m$. At the same time, if agents care about the level of m because they want to get rid of cash they have, the effect of m shouldn't depend on s, as long as $s \leq m$.

[36]If households do not want to run out of cash, higher s increases the probability of card payments, but the effect of s is smaller as m grows. At the same time, higher m decreases the probability of a card payment, and it decreases it more when s is larger (as one abandons the region when $m - s \simeq 0$).

FIGURE A.1: Card acceptance, payment choices and cash management.

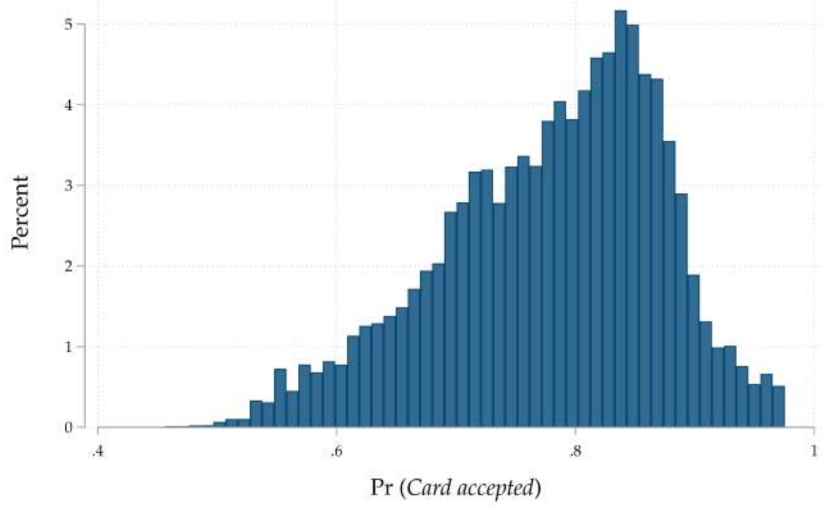


Note: The left panel displays the shares of households paying using cards for bins defined in terms of cash holdings remaining in case agents settle the payment using cash (*implied residual cash holdings* $m' = m - s$), for two groups of individual respectively exposed to a card acceptance rate lower (higher) than the median one. A nonparametric fit ($h = 5$) with 95% confidence intervals is overlaid to the plot. Only unconstrained transactions are considered, and transactions with $m = s$ are omitted. The right panel displays the probability of withdrawing during the day of the survey as a function of m, i.e., the initial level of cash balances. Two nonparametric fits with 95% confidence intervals are overlaid to each plot.
Data from ECB payment diaries: SUCH (2016) and SPACE (2019 and 2021-22).

not accepted at the point of sale. There are two ways to avoid little cash on hand: agents can either use cards when s is very close to m or visit ATMs way before they reach $m = 0$. Our data enables us to understand if the households' precautionary motive for holding cash is driven (at least to some extent) by imperfect card acceptance. We do this by splitting the sample in two groups of households according to the card acceptance rate they are exposed to.[37] Figure A.1 shows how the payment choices and cash management of these two groups of households differ in the ways we hypothesized above. In the left panel, we display a split-sample version of the right panel of Figure 2. The Figure shows that the probability of using cards rises as $s \to m$ especially for households exposed to low acceptance rates; in other words, imperfect acceptance is at least partially driving the rise in the probability of card usage as $s \to m$ we described in Section 2. In the right panel of Figure A.1, we display the probability of performing at least a cash withdrawal during the day of the survey, as a function of cash holdings at the beginning of the day, for the two groups of households: the graph shows that for households exposed to lower card acceptance rates the probability of withdrawing cash spikes up when m is low, while this does not apply to households exposed to high card acceptance. Taken together, the two plots suggest that households want to hold

[37]We describe how to compute individual-specific expected acceptance rates in Appendix A.4.

FIGURE A.2: Distribution of predicted card acceptance probabilities.



low amounts of cash when card acceptance is far from being universal, since being matched with a non-accepting vendor in those circumstances would lead to either i) the impossibility to carry out the desired transaction, or ii) the need to rush to an ATM before going back to the store and completing the purchase.

A.4 Expected card acceptance

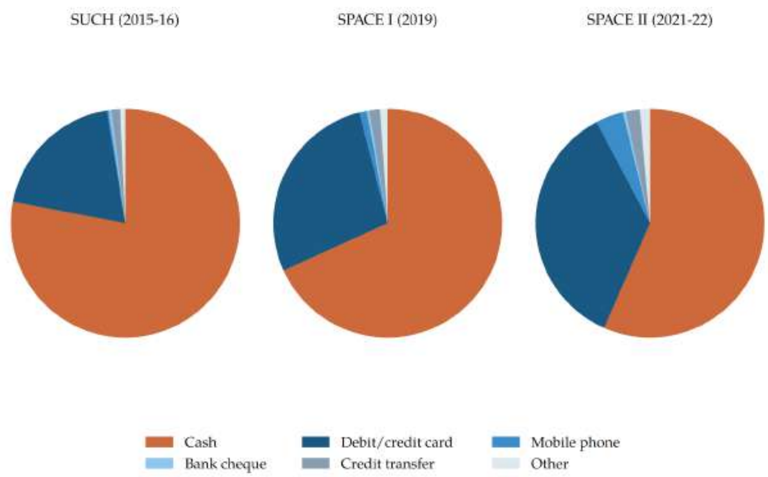
Different individuals are exposed to different card acceptance rates. This depends on the area they live in, as well as on their demographic characteristics which may be correlated with their shopping behavior and therefore with the payment method acceptance policies of the shops they visit. We exploit information on the acceptance of card payments for observed transactions in order to estimate *expected card acceptance rates*, which we use as proxies of perceived acceptance probabilities. For any individual i and for any transaction $t \in \{1, ..., \mathcal{T}_i\}$, we observe Φ_{it}, a dummy variable equal to one if cards were accepted at the point of sale and equal to zero otherwise. We estimate a logit model of the form

$$\Pr(\Phi_{it} = 1) = \frac{1}{1 + \exp(\mathbf{D}_i \boldsymbol{\beta})}, \tag{14}$$

where $\mathbf{D}_i$ is a vector of demographic characteristics of individual i (region, age, sex, education, year surveyed). We then compute predicted probabilities $\widehat{\Phi}_{it}$, i.e., the expected card acceptance rate for any individual in our data. We display the distribution of expected card acceptance rates in Figure A.2.

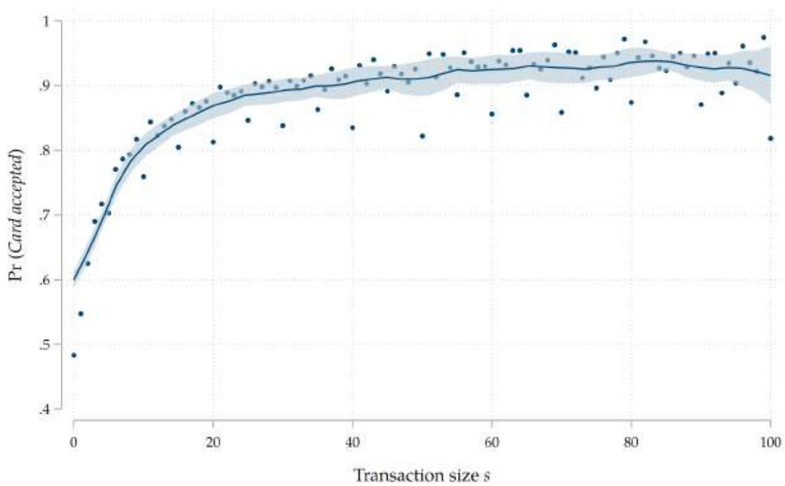
A.5 Additional figures

FIGURE A.3: Payment methods usage in different waves.



Note: This plot shows the portion of payments settled with each payment method across the three waves. Credit and debit cards are bundled together for comparability, as in wave 2 (SPACE I) it was not asked if the card used was a debit or a credit one.

Figure A.4: Card acceptance for different transaction sizes s



Note: Transaction sizes are rounded to the closest integer. In orange, I display for each binned transaction size the share of transactions for which the merchant was willing to accept cashless methods. This is the sum of transactions settled using cashless methods and transactions settled in cash for which the respondent said that cashless methods were accepted at the store. As non-response over cashless acceptance is non-negligible, these cashless acceptance rates are downward biased. In blue, I display for each binned transaction size the share of payments carried out using cashless methods conditional on cashless payments being accepted by the shop and on the respondent having access to at least a cashless payment instrument.

Figure A.5: Share of cash payments for different m and s. Zooming in on smaller transactions/cash holdings levels.

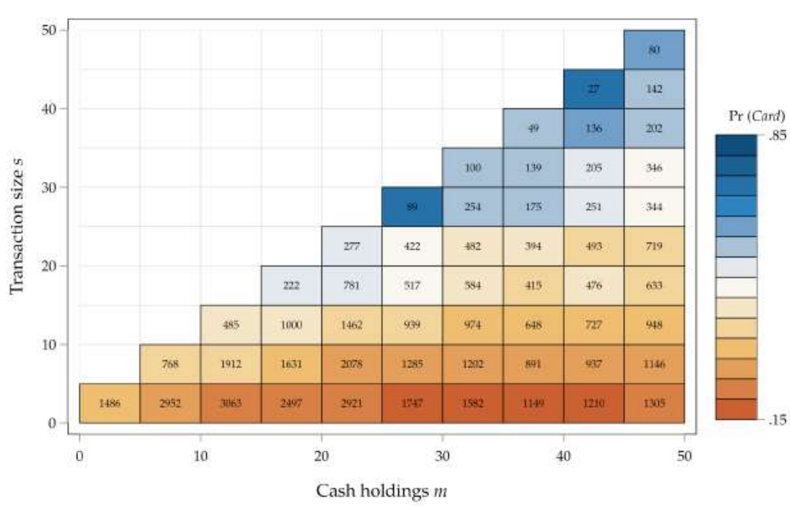


FIGURE A.6: Share of cash payments for different m and s. Including larger transactions and cash holdings.

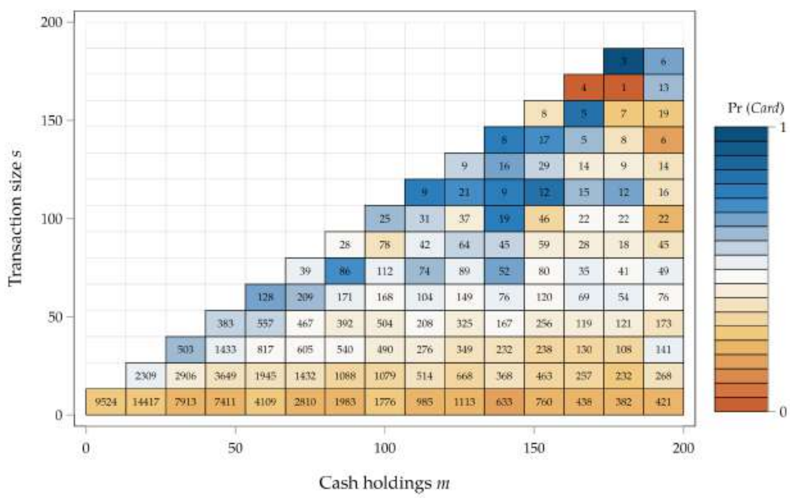
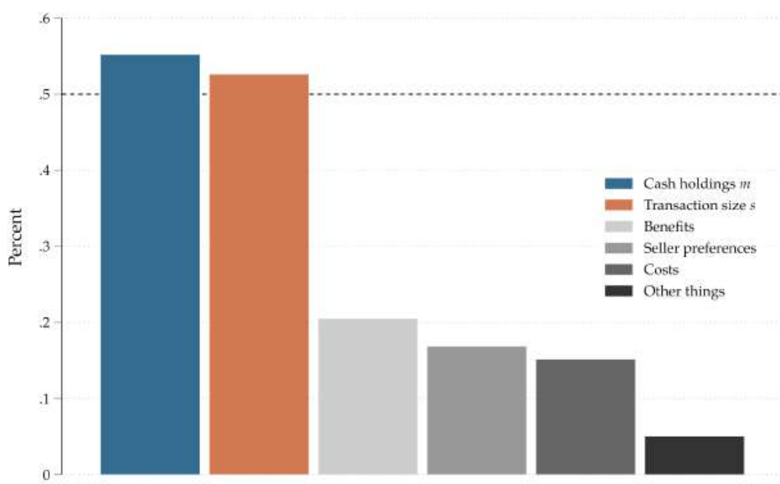
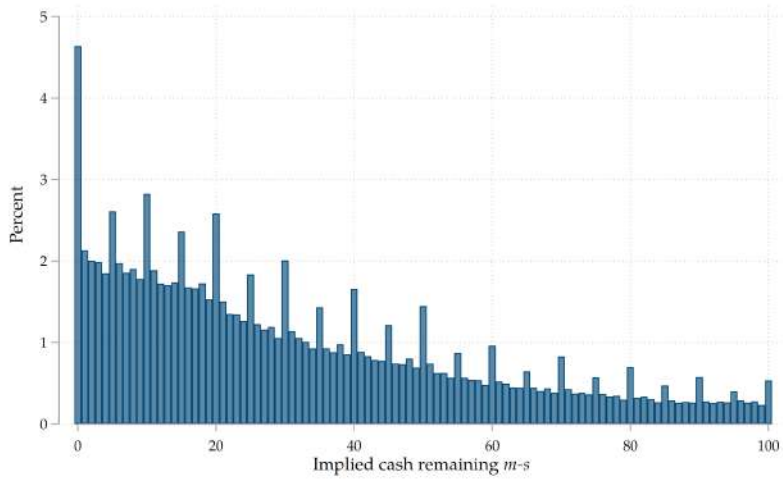


FIGURE A.7: Reported determinants of payment method decisions.



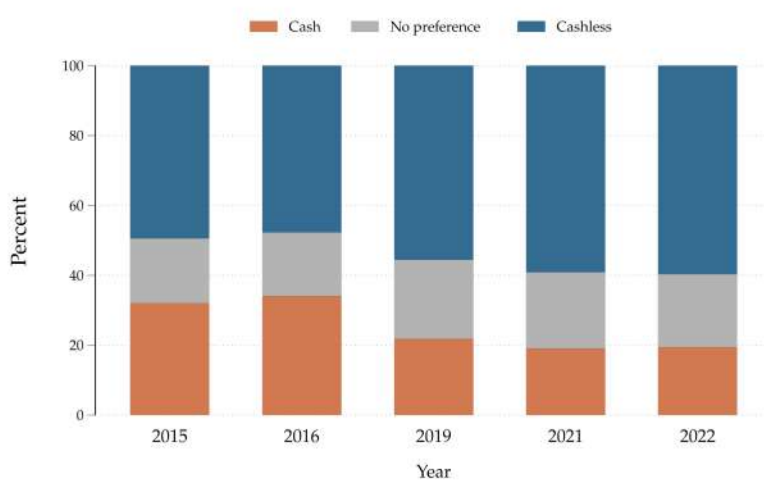
Note: This graph displays the shares of households reporting that a certain factor influences their payment decision. The question respondents answered was: "*Which of the following influences your decision to pay with cash or card or other non-cash payment methods?*". Multiple responses are possible. *Source: ECB SUCH (2016) Data*.

Figure A.8: Distribution on cash remaining $m - s$.



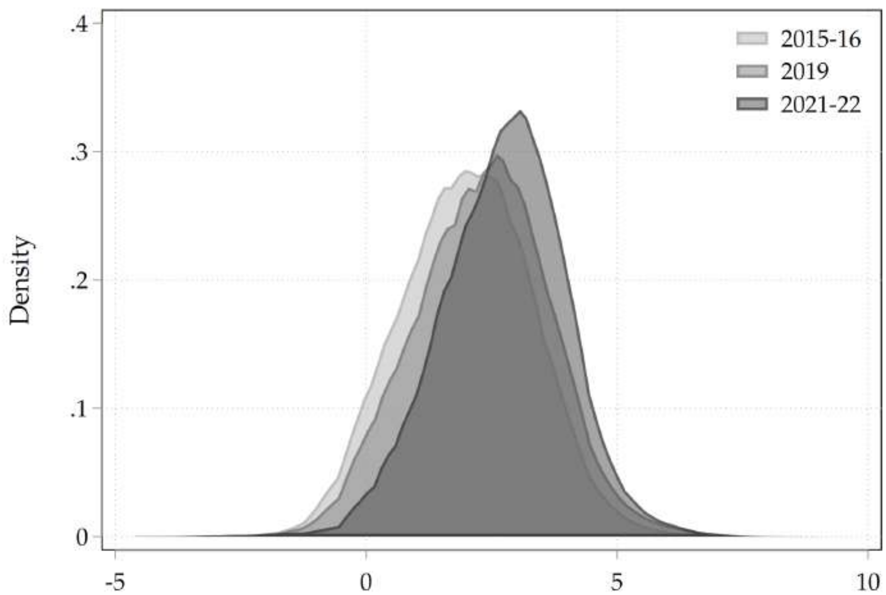
Note: Histogram for implied cash remaining, given by the value of cash holdings m at the moment a transaction is carried out, minus the value of the transaction itself s. I focus on transactions for which there is no uncertainty concerning the amount of cash on hand.

Figure A.9: Payment preferences over the years.



Note: This Figure shows the yearly distribution of answers to the question “If you were offered various payment methods in a shop, what would be your preference?”.

Figure A.10: Payment size distribution (EUR, logs)



B Theoretical appendix

B.1 Proof of Lemma 1

If $p(m,s) = 0$, it means that $v(m-s) \leq v(m) + \kappa$. But then $v(m-s') \leq v(m-s) \leq v(m) + \kappa$ too if v is weakly decreasing. The second result follows from the same logic.

B.2 Proof of Lemma 2

Consider payments of size $s \in [m - \underline{m}, m]$. Agents are indifferent between using cash and cards if $m = \tilde{m}$, where $\tilde{m}$ solves $v(\tilde{m}) = v^* + b - \kappa$ and it is independent of s. As $v(m)$ is decreasing, $p(m,s) = 1$ for $m > \tilde{m}$ and $p(m,s) = 0$ otherwise. A solution to $v(\tilde{m}) = v^* + b - \kappa$ exists if and only if $\kappa < b$, as $v(m) \in [v^*, v^* + b]$. Since i) v is weakly decreasing an continuous, ii) $v(\underline{m}) = v^* + b$, and iii) $v(m^*) = v^*$, by the intermediate value theorem a solution $\tilde{m} \in (\underline{m}, m^*)$ exists. If $\kappa > b$, $v(m) > v^* + b - \kappa$ for any m, hence $p(m,s) = 0$ for all m; if $\kappa < 0$, $v(m) < v^* + b - \kappa$ for any m, hence $p(m,s) = 1$ for all m.

B.3 Proof of Proposition 1

Result (1) arises naturally as a consequence of Lemma 1 and Lemma 2. From Lemma 2 we know that for $s > m - \underline{m}$ cards will be employed when $m > \tilde{m}$; hence $\underline{s}(m) \leq m - \underline{m}$. In particular, we will have that $\underline{s}(m) < m - \underline{m}$ whenever

$$v(m-s) > v(m) + \kappa,$$

for some $m > \tilde{m}$, $s < m - \underline{m}$. Then, for any $m > \tilde{m}$, $\underline{s}(m)$ is the solution to

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

which can be rewritten as

$$\underline{s}(m) = m - v^{-1}\left(v(m) + \kappa\right),$$

where $v^{-1}(v(m)+\kappa)$ is well-defined (it is a singleton) as v is strictly decreasing (hence invertible) on $[\underline{m}, m^*]$, i.e., there exist a unique $\hat{m}(m)$ such that $v(\hat{m}(m)) = v(m) + \kappa < v^* + b$. Also notice that

$$\lim_{m \to \tilde{m}_+} \underline{s}(m) = \tilde{m} - \lim_{m \to \tilde{m}_+} v^{-1}(v(m) + \kappa) = \tilde{m} - v^{-1}(v^* + b) = \tilde{m} - \underline{m},$$

i.e., the smallest transaction that is paid with cash for $m \to \tilde{m}$ is equal to $\tilde{m} - \underline{m}$. Also notice that if we differentiate (7) we obtain

$$\underline{s}'(m) = 1 - (v^{-1})'(v(m) + \kappa)\, v'(m).$$

Using the inverse function theorem, this yields

$$\underline{s}'(m) = 1 - \frac{v'(m)}{v'(v^{-1}(v(m) + \kappa))}.$$

Let $\hat{m}(m)$ be the solution to $v(\hat{m}(m)) = v(m) + \kappa$. This leaves us with

$$\underline{s}'(m) = 1 - \frac{v'(m)}{v'(\hat{m}(m))}.$$

If v is strictly convex for $m > \tilde{m}$, v' is decreasing in absolute value. Given that $\hat{m}(m) < m$, we have that $\underline{s}'(m) > 0$. Since v is strictly decreasing, $\underline{s}'(m) < 1$. Moreover, since $\lim_{m \to m^*} v'(m) = 0$, we have that $\lim_{m \to m^*} \underline{s}'(m) = 1$.

B.4 Derivation of Equation (8)

We show how to derive (8), the functional equation whose solution is the stationary distribution of cash holdings $h(m)$. We have that

$$\begin{aligned} h(m, t + \Delta) = {} & (1 - \lambda\Delta) h(m, t) + \\ & + \lambda\Delta h(m, t)\,(1 - F(m)) + \\ & + \lambda\Delta h(m, t) \int_0^m f(s) \phi p(m, s) ds + \\ & + \lambda\Delta \int_m^{m^*} h(m', t) f(m' - m) \big(1 - \phi p(m', m' - m)\big)\, dm' \end{aligned}$$

Removing time indices and rearranging, we obtain

$$h(m,t)\lambda\Delta\left(F(m)-\int_0^m f(s)\phi p(m,s)ds\right)=\lambda\Delta\int_m^{m^*} h(m',t)f(m'-m)\left(1-\phi p(m',m'-m)\right)dm'$$

which yields the desired result.

B.5 Derivation of Equation (9)

We show how to derive (9), the functional equation whose solution is the function $t(m)$ which yields the average time to the next withdrawal as a function of current cash holdings m. We start from a discrete-time version of the equation and then take its continuous time limit. We have

$$\begin{aligned}t(m)=&(1-\lambda\Delta)(\Delta+t(m))+\\&+\lambda\Delta(1-F(m))(\Delta+t(m))+\\&+\lambda\Delta\int_0^{m-\underline{m}} f(s)(1-\phi p(m,s))[\Delta+t(m-s)]\,ds+\\&+\lambda\Delta\int_{m-\underline{m}}^{m} f(s)(1-\phi p(m,s))\,ds\cdot 0+\\&+\lambda\Delta\int_0^m f(s)\phi p(m,s)[\Delta+t(m)]\,ds.\end{aligned}$$

Rearranging, we obtain

$$\begin{aligned}t(m)\lambda\Delta\left(F(m)-\int_0^m f(s)\phi p(m,s)ds\right)=&\,\Delta-\lambda\Delta^2+\\&+\lambda\Delta^2(1-F(m))+\\&+\lambda\Delta^2\int_0^{m-\underline{m}} f(s)(1-\phi p(m,s))\,ds+\\&+\lambda\Delta\int_0^{m-\underline{m}} f(s)(1-\phi p(m,s))\,t(m-s)ds+\\&+\lambda\Delta^2\int_0^m f(s)\phi p(m,s)ds.\end{aligned}$$

Dividing everything by Δ we get

$$
\begin{aligned}
t(m)\lambda\left(F(m)-\int_0^m f(s)\phi p(m,s)ds\right) = 1-\lambda\Delta+ \\
&+\lambda\Delta\left(1-F(m)\right)+ \\
&+\lambda\Delta\int_0^{m-\underline{m}} f(s)\left(1-\phi p(m,s)\right)ds+ \\
&+\lambda\int_0^{m-\underline{m}} f(s)\left(1-\phi p(m,s)\right)t(m-s)ds+ \\
&+\lambda\Delta\int_0^{m} f(s)\phi p(m,s)\left[\Delta+t(m)\right]ds,
\end{aligned}
$$

and taking limits for $\Delta \to 0$ we finally obtain

$$
t(m)=\frac{1+\lambda\int_0^{m-\underline{m}} f(s)\left(1-\phi p(m,s)\right)t(m-s)ds}{\lambda\left[F(m)-\int_0^m f(s)\phi p(m,s)ds\right]},
$$

or, in terms of implied cash holdings $m'=m-s$,

$$
t(m)=\frac{1+\lambda\int_{\underline{m}}^{m} f(m-m')\left(1-\phi p(m,m-m')\right)t(m')dm'}{\lambda\left[F(m)-\int_0^m f(m-m')\phi p(m,m')dm'\right]}.
$$

B.6 Model-implied moments: additional details

Here, we provide additional details on the computation of model-implied moments, complementing Section 3.2.

Computation of $\underline{M}$ and W. We now illustrate how 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. To do that, we need to compute the stationary distribution of cash balances the moment *before* a payment that triggers a withdrawal takes place. Such a distribution is denoted by $h_w(m)$ and given by

$$
h_w(m)=\frac{h(m)\left(\int_{m-\underline{m}}^{m} f(s)\left(1-\phi p(m,s)\right)ds\right)}{\int_{\underline{m}}^{m^*} h(m)\left(\int_{m-\underline{m}}^{m} f(s)\left(1-\phi p(m,s)\right)ds\right)dm+h(m^*)\left(\int_{m^*-\underline{m}}^{m^*} f(s)\left(1-\phi p(m^*,s)\right)ds\right)},
$$

where the numerator gives the flows into withdrawing coming from cash holdings m and the denominator represents aggregate flows into withdrawing. The boundary condition

$\int_{\underline{m}}^{m^*} h_w(m)dm + h_w(m^*) = 1$ helps us pinning down the mass point $h_w(m^*)$. We can then use this probability distribution to compute $\underline{M}$. An extra step is involved: for any m, we should compute the expected value of s given that a withdrawal took place after a payment before which the individual had m on hand, and subtract it from m to obtain the amount of cash holdings $m - s$ right before the withdrawal took place (i.e., after the payment was settled using cash). We obtain

$$\underline{M} = \int_{\underline{m}}^{m^*} h_w(m) \left[\frac{\int_{m-\underline{m}}^{m} f(s)(m-s)ds}{\int_{m-\underline{m}}^{m} f(s)ds} \right] dm + h_w(m^*) \left[\frac{\int_{m^*-\underline{m}}^{m^*} f(s)(m^*-s)ds}{\int_{m^*-\underline{m}}^{m^*} f(s)ds} \right], \quad (15)$$

which implies an average withdrawal size $W = m^* - \underline{M}$.

Computation of γ_n and $\widetilde{\gamma}_n$. The statistics γ_n and $\widetilde{\gamma}_n$, which measure the share of purchases settled with cards (both overall and when both payment methods were available) can be computed through a slight modification of (10) and (11). The only difference is that now we don't consider the size of each purchase when computing the share. The card share of purchases γ is given by

$$\gamma_n = \frac{\lambda\phi \left(\int_{\underline{m}}^{m^*} h(m)\gamma_n(m)dm + h(m^*)\gamma_n(m^*) \right)}{e}, \quad (16)$$

where $\gamma_n(m) = \int_0^m f(s)p(m,s)ds + (1 - F(m))$ is the share of purchases 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 purchases $\widetilde{\gamma}_n$ is computed as

$$\widetilde{\gamma}_n = \frac{\lambda\phi \left(\int_{\underline{m}}^{m^*} h(m) \left(\int_0^m f(s)p(m,s)ds \right) dm + h(m^*) \left(\int_0^{m^*} f(s)p(m^*,s)ds \right) \right)}{\lambda\phi \left(\int_{\underline{m}}^{m^*} h(m) \left(\int_0^m f(s)ds \right) dm + h(m^*) \left(\int_0^{m^*} f(s)ds \right) \right)}. \quad (17)$$

B.7 Card usage probabilities as a function of m, s and $m' = m - s$

We can compute the probability of cards being used as a function of some important determinants of payment choices, namely m, s and $m' = m - s$. Computing such objects requires knowing i) the invariant distribution of cash holdings $h(m)$, ii) the size distribution of payments $f(s)$, and iii) payment choice probabilities $p(m, s)$. For each of these, we can compute both the *overall* probability of card usage and the probability *conditional* on having both options available (for *unforced* purchases). We start from $\mathrm{Pr}_{\text{ccard}}(s)$, the probability of a card payment when agents face a purchase of size s, which is given by

$$\mathrm{Pr}_{\text{card}}(s) = \phi \left(H(s) + \int_s^{m^*} h(m)p(m, s)dm + h(m^*)p(m^*, s) \right), \tag{18}$$

where H is the cdf associated with the invariant distribution of cash holdings h. Cards are used to settle a purchase of size s whenever i) they are accepted, and ii) either cash holdings are not enough to cover for the transaction, or they are sufficient but cards are chosen nonetheless. The probability of card usage to settle a purchase of size s for an unforced purchase is instead given by

$$\widetilde{\mathrm{Pr}}_{\text{card}}(s) = \frac{\phi \left(\int_s^{m^*} h(m)p(m, s)dm + h(m^*)p(m^*, s) \right)}{\phi \left(1 - H(s)\right)}. \tag{19}$$

Similarly, the unconditional probability $\mathrm{Pr}_{\text{card}}(m)$ of using cards when having m cash balances on hand is given by

$$\mathrm{Pr}_{\text{card}}(m) = \phi \left(\int_0^{m} f(s)p(m, s)ds + (1 - F(m)) \right), \tag{20}$$

while its counterpart for unforced purchases is given by

$$\widetilde{\mathrm{Pr}}_{\text{card}}(m) = \frac{\phi \int_0^{m} f(s)p(m, s)ds}{\phi F(m)}. \tag{21}$$

Finally, we can write $\mathrm{Pr}_{\text{card}}(m')$, the probability of card usage conditional on implied cash remaining in case of a cash payment being equal to $m' = m - s > 0$. Notice that since we focus on $m' > 0$, we only compute this statistic for unforced purchases, i.e.,

$$\widetilde{\Pr}_{\text{card}}(m') = \frac{\phi\left(\int_{m'}^{m^*} h(m)f(m-m')p(m,m-m')dm + h(m^*)f(m^*-m')p(m^*,m^*-m')\right)}{\phi\left(\int_{m'}^{m^*} h(m)f(m-m')dm + h(m^*)f(m^*-m')\right)}. \tag{22}$$

C Calibration details

Calibrating the fixed cost b. We want our estimation results to yield a reasonable value for R, the opportunity cost of holding cash, as it should be of the same order of magnitude of yearly interest rates. Its level can be higher than interest rates as it also includes other costs of holding cash in addition to foregone interest earnings, such as the probability that agents lose their wallets or the eventuality of a cash theft. In order to make sure that R is of the appropriate magnitude and that at the same time our estimation targets are matched, we take as a benchmark the basic BT model and we focus on average cash holdings divided by daily cash expenditure. Let $\widetilde{M}$ be our target value obtained from the data. Recall that in the BT model, $M/c = \sqrt{b/2Rc}$, where c are cash expenditures per year. Average balances relative to *daily* expenditure would be given by

$$\frac{M}{c/365} = 365\sqrt{\frac{b}{2Rc}},$$

and given that we normalize yearly expenditure to $c = 365$ we get

$$M = \sqrt{365}\sqrt{\frac{b}{2R}}, \implies 2M^2 = 365\frac{b}{R}.$$

If we target a level of average cash balances relative to daily cash expenditure $\widetilde{M}$, we need to set $\frac{b}{R} \approx \frac{2\widetilde{M}^2}{365} \approx 0.00548\widetilde{M}^2$. Given that $\widetilde{M}$ is typically in the order of 4-5 in our data, we will need to set b much smaller than our desired R, by a factor given here. Of course, in our model average cash holdings will not necessarily be the same that would emerge in the BT model, which we only use as a useful benchmark in order to normalize b.

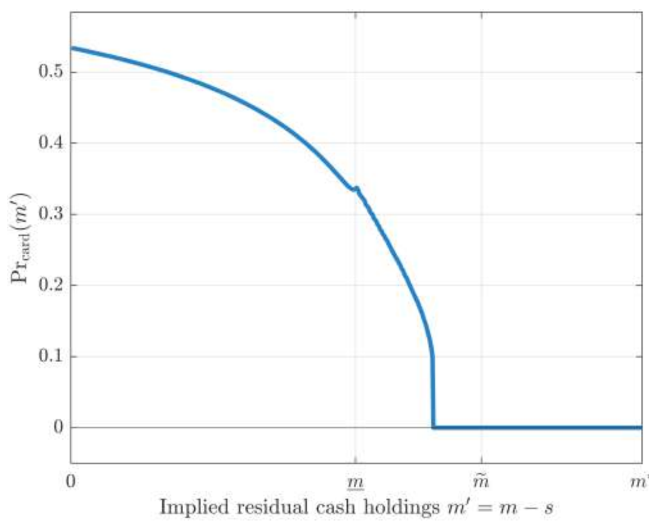
Table 4: Accounting identity and adjustment of n.

	Time period		
	2015-16	2019	2021-22
Data			
Daily consumption expenditure (EUR) e	32.83	45.81	61.63
Credit share of purchases γ	0.45	0.52	0.57
Average withdrawal (EUR) W	59.11	77.64	93.04
N. withdrawals per year (data) n	36.61	52.69	90.37
$nW/(1-\gamma)365e$	0.33	0.51	0.87
Adjustment using acc. identity			
N. withdrawals per year (implied) $\widetilde{n}$	110.80	102.68	103.73
$n/\widetilde{n}$	0.33	0.51	0.87
Adjusted n. withdrawals per year n^*	96.54	89.46	90.37

Note: The implied number of withdrawals under (**??**) is $\widetilde{n} = \frac{(1-\gamma)365e}{W}$.

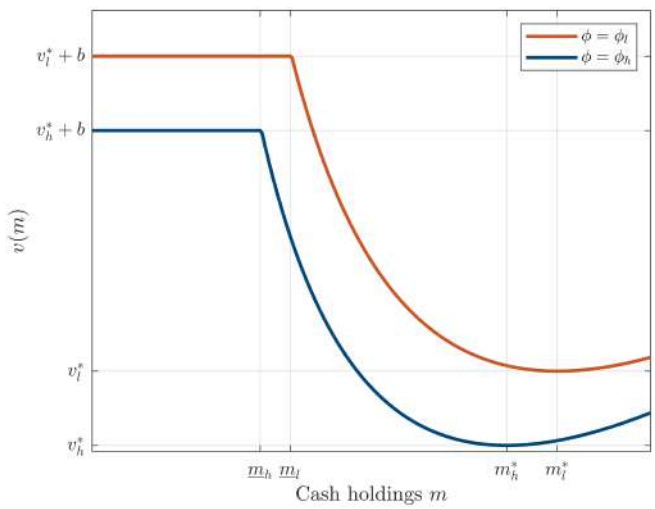
D Theoretical model: additional figures

Figure D.1: Probability of card usage as a function of implied residual cash balances.



Note: The graph shows the model-implied predicted probability $\widetilde{\mathrm{Pr}}_{\text{card}}(m')$ of card usage as a function of implied remaining cash holdings if the purchase is settled in cash $m' = m - s$. $\underline{m}'$ is the smallest level of implied remaining cash holdings that triggers some card usage. Parameters are those obtained from the calibration of the model for 2021-22 discussed in Section 4.

FIGURE D.2: The effect of card acceptance in the model.



Note: The figure displays the value function $v(m)$ for two values of the card acceptance rate ϕ, with ϕ_l denoting low card acceptance and ϕ_h denoting high card acceptance. To produce the plots, we set $\phi_l = 0.7$ and $\phi_h = 0.85$, and we keep all the other parameters at their levels obtained from the calibration of the model for 2021-22 discussed in Section 4.

FIGURE D.3: Decomposition of total cost into its individual components.