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ASSESSING CONSUMER CBDC ADOPTION IN LUXEMBOURG: A MICRO-SIMULATION APPROACH

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Assessing consumer CBDC adoption in Luxembourg: a micro-simulation approach*

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Abstract

We use micro-simulations to estimate consumer adoption of a central bank digital currency (CBDC) for payments. This requires extending a theoretical model of consumer choice among payment methods with a measure of individual digital preferences. The model defines four types of consumers with different propensities to adopt CBDC. We use data from the 2022 SPACE study of payment attitudes to simulate individual consumer CBDC take-up and then aggregate. Our micro-simulation classifies 1% of consumers as *cash-only*, 22% as *cash-preferring*, 29% as *cashless-preferring* and 47% as *cashless-only*. Our theoretical results suggest that if CBDC is accepted by all retailers, then *cashless-preferring* consumers will adopt it instead of cash, but adoption by other consumers would also depend on CBDC design, cost, security and their use of credit cards. Assuming CBDC is universally accepted and can be adopted at no cost, we consider two alternative designs for the CBDC wallet. The first can fund CBDC transactions by drawing cash directly from the user's bank payment account, which results in consumers executing 24% of the value of their total payments in CBDC. The second design also funds CBDC transactions via a direct link to consumer credit (e.g. drawing on the user's credit card), which results in consumers executing 92% of the value of their total payments in CBDC.

Keywords: CBDC, digital euro, money demand, payments, structural model, micro-simulation

JEL classification: E41, E42, E47.

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Résumé non-téchnique

En octobre 2023, la Banque centrale européenne (BCE) et les banques centrales nationales de la zone euro ont lancé la phase préparatoire de l'euro numérique en vue d'une émission éventuelle. L'euro numérique serait un moyen de paiement électronique mis gratuitement à la disposition de tous, comme les espèces aujourd'hui. Il s'agirait d'une monnaie numérique de banque centrale (en anglais *central bank digital currency* ou CBDC) qui bénéficiera du statut de cours légal, contrairement à la monnaie des banques commerciales (c'est-à-dire, les dépôts bancaires avec des moyens de paiement attachés: cartes de débit, cartes de crédit, etc.).

Cette étude évalue la demande au Luxembourg pour une CBDC en tant que moyen de paiement. Nous appliquons des techniques de micro-simulation pour estimer le taux d'adoption de la CBDC à partir d'un modèle théorique du choix des consommateurs entre différents moyens de paiement (espèces, cartes de débit et de crédit) en tenant compte des caractéristiques des différents moyens de paiement (par exemple, le coût, la sécurité, l'acceptation par les commerçants) et les préférences des consommateurs pour les versions numériques de certains biens et services.

En utilisant les données pour le Luxembourg de l'étude SPACE sur les attitudes de paiement des consommateurs dans la zone euro, nous estimons les préférences digitales individuelles et les combinons avec les choix de méthodes de paiement déclarées par les consommateurs pour classer ces derniers en quatre types. Étant donné que chaque type a une propension différente à adopter une CBDC, nous simulons l'adoption individuelle et déduisons l'impact agrégé sous différentes hypothèses quant à la mise en place de la CBDC.

Selon nos estimations, 1 % des consommateurs paient uniquement par espèces, 22 % préférent payer par espéces mais utilisent également les paiements numériques, 28 % préférent les paiements numériques mais utilisent aussi les espèces et 49 % utilisent exclusivement les paiements numériques. Les consommateurs qui n'utilisent que des espèces sont généralement des femmes, ont entre 45 et 75 ans, déclarent qu'ils habitent des zones rurales et participent plus rarement au marché du travail.

Selon nos résultats théoriques, si la CBDC est acceptée par les commerçants, alors les consommateurs qui préfèrent les paiements numériques utiliseront la CBDC à la place des

espèces. Cependant, le taux d'adoption parmi les autres types de consommateur pourrait aussi dépendre des caractéristiques opérationnelles de la CBDC, de son coût, de sa sécurité et de la part des paiements qu'ils effectuent par des cartes de crédit. Nous considérons des scénarios avec différents paramétrages de ces conditions. Dans le scénario *débit en cascade*, le portefeuille CBDC peut se réapprovi-sionner automatiquement en débitant un compte de paiement associé (par exemple, un compte courant chez une banque). Dans ce cas, une transaction en CBDC sera toujours possible à condition qu'il y ait assez de fonds sur le compte de paiement associé. Dans ce scénario, si le réapprovisionnement du portefeuille est possible sans coût, alors les consommateurs au Luxembourg effectueraient 24 % de la valeur totale de leurs paiements en CBDC. Par contre, si le réapprovisionnement du portefeuille devient coûteux et le montant dans le portefeuille CBDC est limité à 3 000 euros, alors seulement 5 à 15 % de la valeur totale des paiements serait exécuté en CBDC.

Dans le scénario *crédit en cascade*, un portefeuille CBDC qui ne contient pas assez de fonds pour exécuter un paiement pourrait également se réapprovisionner automatiquement par du crédit (y compris par les cartes de crédit standard appartenant au consommateur). Dans ce scénario, si le réapprovisionnement du portefeuille est possible sans coût, alors les consommateurs au Luxembourg effectueraient 92 % de la valeur totale de leurs paiements en CBDC. Si le réapprovisionnement du portefeuille devient coûteux et le montant dans le portefeuille CBDC est limité à 3 000 euros, alors la part des paiements executés avec la CBDC se situe dans l'intervalle entre 16 % et 48 %.

Bien que notre analyse se concentre sur la demande de CBDC au Luxembourg, des travaux futurs envisagent l'extension à d'autres pays de la zone euro ainsi que l'analyse de la demande de CBDC en tant que réserve de valeur.

Contents

1 Introduction

In October 2021, the European Central Bank (ECB) and euro area national central banks (NCBs) launched the investigation phase of a project to study the feasibility of complementing cash with a central bank digital currency (ECB (2020); ECB (2023)). In 2023, the European Commission put forward a legislative proposal that could serve as the basis for the potential issue of a digital euro[1] and the ECB launched the preparation phase of the project, in order to lay the groundwork for the potential issuance of a digital euro (ECB (2024)).

This paper assesses demand for a central bank digital currency (CBDC) from consumers in Luxembourg under alternative settings. The literature identified several determinants of consumer choice among means of payment (Kosse (2014)). Some studies focused on the characteristics of different means of payment, such as cost, security or convenience (Schuh and Stavins (2010), Kahn and Liñares-Zegarra (2016)). Other considered consumer characteristics and cultural background (Kosse and Jansen (2013)), including habits (Van der Cruijsen et al. (2017)), self-control (Hernandez et al. (2017)), attitudes (Doerr et al. (2022)), risk perception (Kosse (2013)) or digital preferences (Giordana and Guarda (2025), Giordana and Guarda (2019)). The present paper builds on this literature to estimate what share of their payments consumers in Luxembourg would make in CBDC.

To estimate CBDC take-up, we implement a micro-simulation based on a theoretical model of consumer choice among payment methods. We adapt Bolt and Chakravorti (2008), focussing on consumer behaviour to consider individual preferences for digital alternatives as well as features of the different means of payment (i.e. cash, debit and credit cards). Using data from the 2022 Study on the payment attitudes of consumers in the euro area (SPACE), we apply the modelling approach in Giordana and Guarda (2025) to estimate individual digital preferences and classify consumers into four types according to their stated payment preferences and reported payment behaviour (i.e. cash-only, cash-preferring, cashless-preferring and cashless-only). Since each consumer type has a different propensity to take up CBDC, we simulate individual take-up and aggregate under alternative CBDC designs. Our focus is on consumer choice, meaning we do not study how the introduction of a CBDC would affect

[1] See "Proposal for a regulation of the European Parliament and of the Council on the establishment of the digital euro" (COM/2023/369 final).

the pricing of payment services or the interest rate on deposits, which are exogenous in our analysis.[2]

Two stylized facts underpin both our theoretical framework and empirical analysis. First, consumers prefer using fewer payment methods, if possible only one, and second, consumers only use several methods if their preferred method is not accepted or is too risky (Meyer and Teppa (2024); Bagnall et al. (2016)). Accordingly, the two-sided market feature of payments constrains consumers to adopt methods accepted by merchants. However, the security risk borne by cash-carrying consumers will constrain some of them to also use cashless payments. Thus, we integrate a parsimony assumption (i.e. linear utility function) with consumers only adopting more than one payment method when constrained.

Our framework is static and therefore ignores the diffusion time of a new payment technology such as a CBDC.[3] However, we acknowledge the costs associated with the discovery and testing of new technologies, as our modelling approach implies a preference for the incumbent method unless the new one is *ex-ante* perceived as superior.[4] In addition, we assume a CBDC will function as a state-of-the-art debit/credit card, although it may be cheaper and more widely accepted due to legal tender status. Limiting the differences between new and incumbent methods to only two dimensions, price and merchant acceptance, would reduce discovery costs and facilitate adoption.

We contribute to the literature estimating consumer CBDC demand for transaction purposes (Huynh et al. (2020), Li (2023), Nocciola and Zamora-Pérez (2024))[5], which claims that cash-like or card-like CBDCs could be designed to be similar to cash or cards. By varying the similarity of CBDC to cash or cards, they argue that CBDC demand would be

[2]For theoretical studies on how the introduction of a CBDC would affect the interest paid on bank deposits in a monopolistic banking system, see Andolfatto (2020), in a competitive system see Keister and Sanches (2022), and in an oligopolistic system see Chiu et al. (2023).

[3]By considering gradual diffusion of new technologies, Nocciola and Zamora-Pérez (2024) show how an environment conducive to the diffusion of mobile payment applications could foster CBDC adoption and usage. Unlike the typical gradual pattern of technology diffusion (Stokey (2021)), when studying the macroeconomic consequences of the transition towards an economy with a CBDC, Assenmacher et al. (2024)'s model predicts an over-shooting of CBDC demand in the short-run.

[4]Abramova et al. (2022) note that 46% of respondents to a survey in Austria report that their satisfaction with available payment methods is the main reason why they are not interested in a digital euro. Survey results for Netherlands indicate that dissatisfaction with existing saving accounts correlates with interest to adopt a hypothetical CBDC savings account (Bijlsma et al. (2021)).

[5]For reviews, see Auer et al. (2022)

driven by consumers who state a preference for cash or by those who state a preference for cards. Instead, we estimate individuals' digital preferences that influence their subjective assessment of the advantage of cashless methods in terms of transaction speed, ease of use and logistic convenience, without influencing their assessment of other attributes (safety, acceptance and budget awareness). Our explicit use of digital preferences allows us to account for some of this unobserved heterogeneity. For example, two different consumers may have a similar assessment of cash and cashless methods along all dimensions listed above, but still choose differently because of their respective digital preferences. In our framework, a consumer whose digital preferences dictate a preference for cash over cashless payments would never switch to a CBDC.[6]

Our micro-simulation results classify 1% of consumers as cash-only, 22% as cash-preferring, 28% as cashless-preferring and 49% as cashless-only. Our theoretical results suggest that if CBDC is accepted by all retailers, then cashless-preferring consumers will switch their cash payments to CBDC, but adoption by other consumer types could depend on CBDC cost and access to credit. Our scenarios reflect alternative settings of these conditions. In particular, the "debit waterfall" allows CBDC payments to be funded from an associated payment account (including bank deposits) if there are insufficient funds for the transaction in the CBDC wallet. In the absence of holding limits, this would lead to consumers in Luxembourg executing 24% of the total value of their payments in CBDC. However, a 3,000 euro holding limit would limit CBDC payments to 5% of the value of all payments, although the exact reduction would depend on the cost of refilling the wallet. Instead, the "credit waterfall" scenario also allows CBDC payments to be funded by credit (including standard credit cards) if there are insufficient funds in the CBDC wallet. In the absence of holding limits, this would lead to consumers in Luxembourg executing 92% of the total value of their payments in CBDC.[7]. However, a €3,000 holding limit would lead to only 16% being executed in CBDC, although the exact reduction would depend on the cost of refilling the wallet. This scenario results in the highest level of CBDC adoption by consumers. While our paper focuses on

[6]Brown et al. (2020) analysed the impact on cash demand from the introduction of contactless debit cards and found a negligible effect for cash-loving consumers.

[7]Using data from the Household Finance and Consumption Survey, Pulina (2023) estimates that close to 84% of households in Luxembourg hold credit cards, well above the euro area average (49%).

Luxembourg, an extension to other euro area countries is straightforward.

The paper is organized as follows. Section 2 identifies digital euro design features relevant for our analysis. Section 3 presents the theoretical model of consumer behaviour defining consumer types. Section 4 presents our empirical estimates of consumer types, CBDC take-up and payments. Finally, section 5 concludes.

2 Digital euro design

On 28 June 2023, the European Commission proposed a regulation of the European Parliament and of the Council on the establishment of the digital euro (COM(2023) 369 final 2023/0212(COD)). This will regulate its essential design features to ensure the use of the euro as a single currency across the euro area.

In the context of this study, the most relevant design aspects are:

1. The digital euro is available to natural and legal persons for the purpose of retail payments.

2. The digital euro is granted legal tender status, which entails its mandatory acceptance by payees (Article 7). However, some exceptions are envisaged (Article 9). For instance, a micro-enterprise may refuse to accept digital euro payment if it accepts comparable digital means of payment. In general, digital euro and euro cash are convertible into each other at par (Article 12). In situations where both digital euro and cash must be accepted, the payer would have the right to choose.

3. The European Central Bank (ECB) should develop instruments to limit the use of the digital euro as a store of value (i.e. holding limits). However, digital euro should not bear interest.

4. All payment service providers (PSPs) in the EU may enter into a contractual relationship with digital euro users to provide digital euro payment services, including enhanced services in addition to basic digital euro payment services. The latter include the “waterfall” and “reverse waterfall” functions, meaning PSPs need to provide defunding and funding functionalities (Article 13). The “waterfall” would be activated

when receipt of a digital euro payment raises the user's digital euro holdings above holding limit. This would trigger automatic defunding, transferring the excess to one of the user's payment accounts (e.g., a commercial bank account). Instead, the "reverse waterfall" would enable users to make a digital euro payment in excess of the holding limit by transferring sufficient funds to cover the shortfall from an associated payment account. No provision in the regulation seems to exclude a "reverse-waterfall" linking a digital euro account to a payment account with access to a credit line or funded by a credit card.

5. Basic digital euro payment services should be provided for free to anybody requesting them, even to natural persons that do not have a non-digital euro payment account or do not wish to hold one (Article 14). In addition, merchant service charges or inter-PSP fees are regulated so that they cannot exceed fees or charges requested for comparable means of payment.

The European Commission proposal clearly intends the holding limits on the digital euro to discourage its use as a store of value. In addition, the obligation that PSPs provide digital euro payment services should ensure that it satisfies state-of-the-art security requirements. In other words, it would be as secure as currently available digital means of payments with the same kind of risks. Legal tender status would be its main distinguishing feature.

3 Consumer choice of payment method: a theoretical framework

We build on Bolt and Chakravorti (2008) and consider a one-period economy where consumers choose how to pay for their consumption of *numeraire* good and do not save. Merchants sell the good and may accept different cashless payment methods in addition to the legal tender (i.e. cash). Banks provide cashless payment services that are not legal tender. To study digital euro take-up, we adapt several of Bolt and Chakravorti (2008)'s assumptions on consumers, merchants and banks. In particular, we modify consumer characteristics and the shocks affecting consumers and represent merchants and banks through exogenous variables and parameters. Thus, we prevent merchants passing payment fees to consumers via price discrimination, and prevent banks charging different fees (and interest rates) for debit and credit cards. There is a single lump-sum fee equal to D to be paid by cash, which only concerns users of payment cards.

Unobserved consumer characteristics are only known by their distribution functions. There are four unknown characteristics: disposable income y, share of income that can only be spent using credit cards ϕ^e, maximum share of cashless payments α and digital preferences β. First, each consumer i receives disposable income y_i, where $(1-\phi_i^e)$ is the share of cash income, which can also be spent using debit cards.[8] These assumptions allow us to reproduce the income distribution estimated on survey data and to distinguish debit from credit cards among cashless methods. Second, each consumer spends a share $1-\alpha_i$ (with $\alpha_i \in [0,1]\,\forall i$) of cash income in *cash-only* merchants (cashless payments are not legal tender). Third, consumers differ in their preferences for payment methods. Those consumers with higher digital preferences (i.e. higher β_i in equation (1) below) prefer cashless methods over cash. Finally, consumers may be mugged with share $1-\rho$ of carried cash being stolen (with $\rho \in [0,1]$ being known and the same for all consumers). Thus, as in Bolt and Chakravorti (2008), cash-carrying consumers could consume more by using cashless payments instead. This assumption allows us to model cashless payments as more secure than cash.[9] The cumulative distribution and density of β are F and f, those of α are G and g, those of y are P and p, and those of ϕ^e are P^e and p^e.

We assume that consumers spend all their income and only choose their payment method to maximize the linear utility function:

$$u_i\left(c_{c,i}, c_{l,i}\right) = \beta_i c_{l,i} + (1-\beta_i)c_{c,i}, \;\; \forall i \leq N \tag{1}$$

where $c_{c,i}$ is consumption paid by cash and $c_{l,i}$ is consumption paid by cashless methods, β_i is a parameter reflecting consumer i preference for cashless payments with $\beta_i \in [0,1]\,\forall i$ and N is total number of consumers.

[8]Bolt and Chakravorti (2008) defined ϕ_i^e as the share of income received at the end of the period and therefore, it could only be spent using credit cards.

[9]There is no need for cashless payments to be riskless for our results to hold.

The linear utility function (1) involves a parsimonious preference assumption if $\beta_i \neq 0.5$, as consumers would prefer to use only one payment instrument. Consumers would only combine payment instruments if they are constrained to do so by merchants (i.e. α random variable), by security considerations (i.e. ρ parameter) or by the share of their income they can only spend with credit cards (i.e. ϕ^e random variable). A digital-averse consumer i (low β_i with respect to ρ) would prefer to spend all income in cash with consumption reaching $\bar{c}_{c,i} = (1-\phi_i^e)\, y_i \rho$. However, only a part of income is received in cash. Therefore, to consume non-cash income, e.g. future income, such a consumer would also use cashless payments (specifically, a credit card) if $D < \min\left(y_i\left(1-\phi_i^e\right), y_i\phi_i^e\right)$ and consumption would increase to $\bar{c}_{l,i} = \phi_i^e y_i - D$. Instead, a digital-loving consumer j (high β_j) would prefer to spend all income using cashless payments with consumption reaching $\bar{c}_{l,j} = y_j - D$ also if $D < \min\left(y_j\left(1-\phi_j^e\right), y_j\phi_j^e\right)$. The latter consumer would only use cash payments if merchants do not accept cashless payments (i.e. $\alpha_j < 1$).

Result 3.1 defines the different consumer types based on the above assumptions. Consumers can be divided in two groups, depending on their value of β: cash-lovers prefer to only pay with cash ($\beta < 0.5$) and cashless-lovers prefer to only pay with cashless methods ($\beta > 0.5$). Within each group, there is a sub-group that is constrained to also use their less preferred payment method because of ρ (security constraint), α (merchant acceptance constraint) or ϕ^e (share of income that can only be spent by credit card). Therefore, we split cash-lovers into two groups: cash-only and cash-preferring. Similarly, cashless-lovers are split into two groups: cashless-only and cashless-preferring. Figure 1 helps to understand the underlying mechanics.

Result 3.1. *Consumer types*

A consumer i with preferences β_i and credit share of income ϕ_i^e is a:

1. *Cash-only, if $\rho > \bar{\rho}_i\left(\beta_i, y_i, \phi_i^e, D\right)$ or $\beta_i < \bar{\beta}_i\left(\rho, y_i, \phi_i^e, D\right)$ or $D > \bar{D}_i$, with $\bar{\rho}_i = \frac{y_i\phi_i^e\beta_i}{D(1-\beta_i)}$, $\bar{\beta}_i = \frac{\rho}{y_i\phi_i^e/D+\rho}$ and $\bar{D}_i = \frac{y_i\phi_i^e\beta_i}{\rho(1-\beta_i)}$ if $\phi_i^e > 0$, or if $\phi_i^e = 0$, $\bar{\rho}_i = \frac{\beta_i}{(1-\beta_i)}$, $\bar{\beta}_i = \bar{\beta} = \frac{\rho}{1+\rho}$ and $\bar{D}_i = \bar{D} = 0$.*

2. *Cash-preferring (using both cash and cashless payments) if $D \leq y_i\left(1-\phi_i^e\right)$ and $\bar{\beta}_i \leq \beta_i \leq 0.5$, with $\bar{\beta}_i = \frac{\rho}{\frac{y_i\phi_i^e}{D}+\rho}$ if $\phi_i^e > 0$ or $\bar{\beta}_i = \bar{\beta} = \frac{\rho}{1+\rho}$ if $\phi_i^e = 0$.*

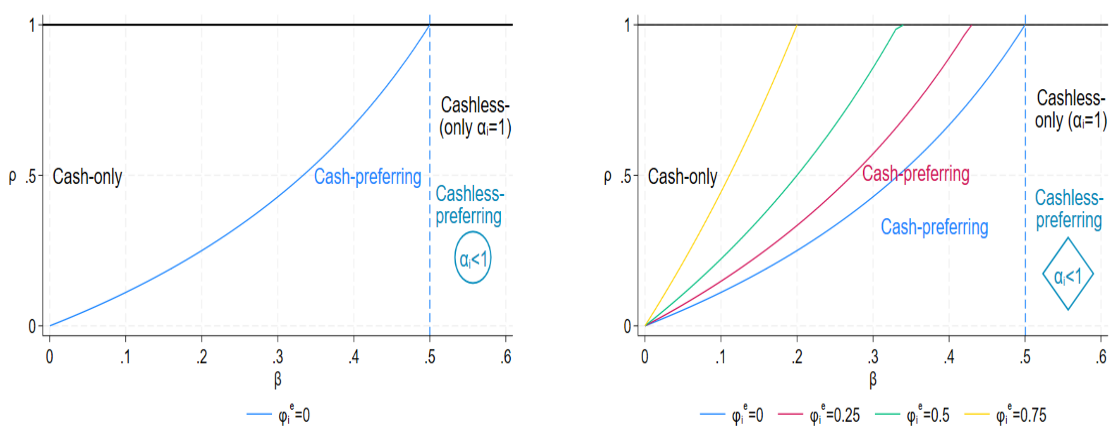
3. Cashless-only if $\beta_i > 0.5$, $D \leq y_i\left(1-\phi_i^e\right)$ and $\alpha_i = 1$.

4. Cashless-preferring if $\beta_i > 0.5$, using cash payments if $D > y_i\left(1-\phi_i^e\right)$ or $\alpha_i = 0$, or using both cash and cashless payments if $D \leq y_i\left(1-\phi_i^e\right)$ and $0 < \alpha_i < 1$.

Proof: see Appendix 6.1.

Figure 1 plots the function $\bar{\rho}\left(\beta_i, y_i, \phi_i^e, D\right)$ indicating the value of ρ for each β_i at which the consumer is indifferent between cash and cashless payments. Several curves are plotted for different values of the ratio $\Theta_i = \frac{D}{y_i \phi_i^e}$, with Figure 1a focussing on the special case where all the income can be spent in cash or via debit cards ($\phi^e = 0$). The trade-offs between digital preferences, perceived risk of cash versus cashless payments and disposable income are clearly visible. On the one hand, every consumer i with $\phi_i^e = 0$ always prefers cashless payments if $\beta_i > 0.5$ or is indifferent if $\beta_i = 0.5$ (vertical dashed line), regardless of ρ. On the other hand, consumer i with $\phi_i^e = 0$ and $\beta_i < 0.5$ only prefers cashless payments if ρ is below $\bar{\rho}\left(\beta_i, y_i, 0, D\right)$ (blue line) because of perceptions that cash is more insecure. Moreover, Figure 1b shows that, for each value of ρ, for higher ϕ_i^e (red, green and yellow lines in Figure 1b) the threshold value $\bar{\beta}_i$ is lower because consumers rely more heavily on credit cards since a higher share of their income cannot be spent as cash or debit cards.

Figure 1: Consumer types and payment method choice

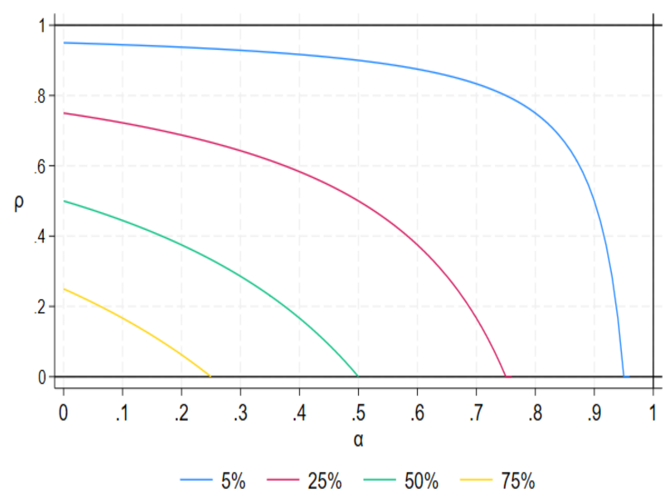


(a) No need for credit ($\phi_i^e = 0$) (b) Credit needed to spend ϕ_i^e of income

If $0 < \alpha_j < 1$, a cashless-preferring consumer j would buy at both cash-only and cashless merchants with consumption at cashless merchants being $\bar{c}_{l,j} = \alpha_j\left[\left(1-\phi_j^e\right)y_j - D\right] + \phi_j^e y_j$

and consumption at cash-only merchants being $\bar{c}_{c,j} = \left[\left(1 - \phi_j^e\right) y_j - D\right] (1 - \alpha_j)\, \rho$. If a legal tender cashless payment (like a CBDC) becomes available, expected consumption increases by $y_j (1 - \alpha_j)(1 - \rho)\left(1 - \phi_j^e\right)$. Note that this only concerns income received in cash, because no CBDC credit is available.[10] Figure 2 shows the combinations of α_i and ρ consistent with a given increase in expected consumption from the introduction of CBDC. For instance, the yellow curve indicates combinations consistent with a consumption increase equivalent to 75% of expected disposable income in cash: $(1 - \alpha_j)(1 - \rho) = 0.75$. We observe a negative relationship between α_i and ρ along the iso-consumption curves. Accordingly, the lower the combined values of α_i and ρ the higher the expected increase in consumption from CBDC introduction.

Figure 2: Consumption increase due to CBDC



3.1 CBDC adoption by consumers

As discussed in section 2, in practice, the digital euro would work as a debit card with legal tender status (eventually enhanced to work as a credit card). Assuming no exceptions to the legal tender condition, introducing CBDC would *de facto* force cash-only merchants to accept cashless payments in CBDC. Accordingly, *cashless-preferring* consumers (see Result 3.1) would be able to make cashless payments for all their consumption even if $\alpha_i = 0$.

[10]However, if PSPs provide a "reverse waterfall" service linked to a credit card, this can finance consumption paid with CBDC.

However, the CBDC would not affect the risk associated with cash payments (i.e. no change in ρ), with no impact on the choices of *cash-only* consumers (see Result 3.1).

Three substitution effects become apparent: cash-for-CBDC, debit-card-for-CBDC and credit-card-for-CBDC (even if CDBC credit is not available).[11] From result 3.1, the extent of substitution would depend, on the one hand, on how digital preferences (β) are distributed across the population, how cash-only restrictions (α) are distributed across the population, and on what share of income can only be spent with credit cards ϕ^e. The fee structure imposed by banks is also relevant. We can think of several alternatives. First, a bundle-fee case, where the CBDC fee provides access to all three payments (CBDC, debit card and credit card) and is not higher than fees on debit or credit cards $D_{CBDC} \leq D$. Second, an individual-fee case, where the CBDC fee is no greater than debit card and credit card fees $D_{CBDC} \leq D$, but only gives access to CBDC with debit and credit cards requiring payment of an additional fee D. We focus on the second alternative as it seems the most plausible. Results are summarized below:

Result 3.2. *Substitution effects and CBDC take-up*

In the individual-fee case, with $0 \leq D_{CBDC} \leq D$

1. ***Cash-for-CBDC*** *substitution affects cashless-preferring consumers, representing the following share of consumers (assuming independence of* β, α, y *and* ϕ^e*):*

$$Pr\left(\bar{\beta}(\rho) \leq \beta \leq 1, \alpha < \Gamma, \phi^e < 1 - \frac{D + D_{CBDC}}{y}\right)$$
$$= \int_{\bar{\beta}(\rho)}^{1} f(\beta)\, k(\beta, \alpha)\, l^0(y, \phi^e)\, d\beta, \tag{2}$$

where $\Gamma = 1 - \frac{\beta}{(1-\beta)\left[\frac{\beta}{(1-\beta)} - \rho\right]} \cdot \frac{D_{CBDC}}{[(1-\phi^e)y - D]}$, *and* $k(\beta, \alpha)$ *and* $l^0(y, \phi^e)$ *are index functions:*

$$k(\beta, \alpha) = \begin{cases} 1 & \textit{if } \alpha < \Gamma \\ 0 & \textit{otherwise} \end{cases} \tag{3}$$

[11] Enlarging the consumer choice set with the introduction of a new alternative is conceptually equivalent to reducing its price from infinity to some relevant value, if the choice set would have already included the alternative.

$$l^0(y,\phi^e)=\begin{cases}1 & \mathit{if}\ \phi^e<1-\frac{D+D_{CBDC}}{y}\\ 0 & \mathit{otherwise}\end{cases} \tag{4}$$

CBDC demand amounts to:

$$\int_{\bar{\beta}(\rho)}^{1}(1-\alpha)\left[(1-\phi^e)\,y-D-D_{CBDC}\right]f(\beta)\,k(\beta,\alpha)\,l^0(y,\phi^e)\,d\beta. \tag{5}$$

2. ***Debit-card-for-CBDC*** *substitution also affects cashless-preferring consumers as in (2). It amounts to:*

$$\int_{\bar{\beta}(\rho)}^{1}\alpha\left[(1-\phi^e)\,y-D-D_{CBDC}\right]f(\beta)\,k(\beta,\alpha)\,l^0(y,\phi^e)\,d\beta. \tag{6}$$

In addition, some cashless-only consumers switch to CBDC from debit cards, see next item.

3. ***Credit-card-for-CBDC*** *substitution occurs even if there is no CBDC credit. It affects both cashless-only and cashless-preferring consumers if their individual parameters respect* $y\phi^e<D-D_{CBDC}$. *The credit-card-for-CBDC substitution effect amounts to:*

$$\int_{\bar{\beta}(\rho)}^{1}(1-\phi^e)\,y\,(D-D_{CBDC})\,f(\beta)\,l^1(y,\phi^e)\,d\beta, \tag{7}$$

where $l^1(y,\phi^e)$ *is an index function:*

$$l^1(\phi,\phi^e)=\begin{cases}1 & \mathit{if}\ \phi^e<\frac{D-D_{CBDC}}{y}\\ 0 & \mathit{otherwise}\end{cases} \tag{8}$$

However, this substitution will imply a switch from debit card payments to CBDC by cashless-only consumers and by cashless-preferring consumers that do not satisfy conditions (3) and (4). Thus, CBDC demand would increase by:

$$\int_{\bar{\beta}(\rho)}^{1}(y-D_{CBDC})\,f(\beta)\,l^1(y,\phi^e)\,d\beta. \tag{9}$$

Proof: see Appendix 6.2.

The parsimony assumption has substantial implications for our theoretical results on CBDC demand. It would lead *cashless-preferring* consumers to switch from both cash and debit card payments to CBDC. In addition, if the CBDC design allows for a wallet and/or a reverse waterfall funded with credit, cashless-preferring consumers would also switch from credit-card payments to CBDC to use a single payment instrument. In such a scenario, where CBDC credit is permitted, the level of the lump-sum fee on CBDC would affect its adoption by *cashless-only* and *cash-preferring* consumers. Again for the sake of parsimony, *cashless-only* consumers switching from credit cards to CBDC payments would lead these consumers to switch from debit cards to CBDC as well, in case they were using them.

3.2 CBDC holding limits

To safeguard financial stability, there will be a limit on the amount of CBDC consumers can hold.[12] Such holding limits introduce frictions that would limit the substitution effects discussed in the previous section. They could also discourage some consumers from adopting the CBDC at all. The frictions would reduce the convenience of CBDC (if the consumer needs to manually recharge the CBDC wallet more often), make transactions slower or less secure (e.g. latency time) or increase transaction fees (if commercial banks charge a fee to automatically refill the CBDC wallet).

To account for these frictions, we assume that each consumer i adopting the CBDC would bear a cost $h(w_i)$, where w_i is the ratio between the income a consumer receives in cash and the holding limit z:

$$h(w_i) = h\left(\frac{(1-\phi_i^e)y_i}{z}\right) = \begin{cases} 0 & \text{if } w_i < 1 \\ (0, +\infty) & \text{if } w_i \geq 1, \text{ with } h' > 0, h'' \leq 0. \end{cases} \tag{10}$$

These frictions would limit the effects described in Result 3.2 (equations (6) and (9)). Moreover, some cashless-preferring consumers would simply not adopt the CBDC. These effects are summarized in the following:

[12] See Article 16 of the draft Regulation referred in Section 2.

Result 3.3. *Holding limits on CBDC would reduce the three effects defined in Result 3.2 (cash-for-CBDC, debit-card-for-CBDC and credit-card-for-CBDC).*

Proof: *Holding limits make conditions (3), (4) and (8) more restrictive as D_{CBDC} is replaced by $D'_{CBDC} = D_{CBDC} + h(w_i)$, where $h(w_i)$ was defined in (10).*

4 Empirical results

We implement a micro-simulation exercise based on the theoretical model (section 3). We use 2022 data from the Study on the payment attitudes of consumers in the euro area (SPACE)[13] to identify consumer types and estimate consumer CBDC demand under alternative designs.

4.1 Digital preferences and consumer types

To estimate the shares of different consumer types defined in our theoretical framework, we rely on reported payment behaviour and stated preferences for cash payments and cashless payments in SPACE data. The SPACE survey data was collected in two rounds between October 2021 and June 2022 and reports on individual payment behaviour among euro area residents by demographic and socio-economic characteristics (ECB (2022)). In Luxembourg, a total of 1008 adults participated in at least one of the survey rounds.

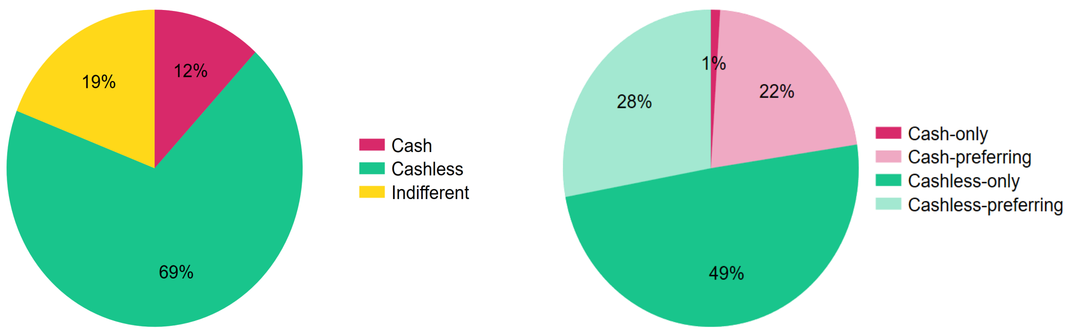
Figure 3a illustrates the frequencies of stated payment method preferences: 69% of Luxembourg residents state they prefer cashless payments, 12% prefer cash payments and 19% are indifferent. To split indifferent consumers between those preferring cash and those preferring cashless payments, we proceed in two steps. First, we adopt the approach in Giordana and Guarda (2025) to measure individual digital preferences using survey data. This assumes that individual choices between traditional and digital versions of goods and services are only partly explained by demographic and socio-economic characteristics, but also driven by latent idiosyncratic factors measuring preferences for digital alternatives. These latent digital preferences are estimated by applying Structural Equation Modelling (SEM)[14] to a set of indicators drawn from the EU survey on Information and Communication Technol-

[13] For details see `https://www.ecb.europa.eu/stats/ecb_surveys/space/html/index.en.html`

[14] For a practitioner-aimed introduction see Kline (2016).

ogy (ICT) usage by individuals and households. These observed indicators are theoretically correlated with the latent factor. Below, we apply the approach in Giordana and Guarda (2025) to the SPACE data.[15]

Figure 3: Stated payment preferences and consumer types



(a) Stated payment preferences

(b) Consumer types

Source: (a) SPACE 2022 wave for Luxembourg; weighted results (question QQ3: "If you were offered various payment methods in a shop, what would be your preference?"). (b) Own calculations using SPACE 2022 wave for Luxembourg; weighted results.

Second, we used the resulting measure of digital preferences to estimate the threshold $\bar{\beta}$ presented in section 3 (see Figure 1, Result 3.1 and associated discussion) by implementing the "signals approach" (Kaminsky et al. (1998)) or "signalling approach" (Detken et al. (2014)), which consists of a grid search over alternative values to find the one that minimises classification errors (after dropping the indifferent cases).[16] In this particular case, we exclude cases who were indifferent between cash and cashless payments and evaluate how effective different values of our measure of digital preferences are to separate those who preferred cashless payments from those who preferred cash payments.[17] We then use the estimated threshold $\hat{\bar{\beta}}$ to also split indifferent consumers into those who prefer cash and those who prefer cashless payments.

Figure 4a plots the estimated density of our measure of digital preferences, which resembles the sum of two Gaussian variables. Figure 4b plots the empirical cumulative distribution

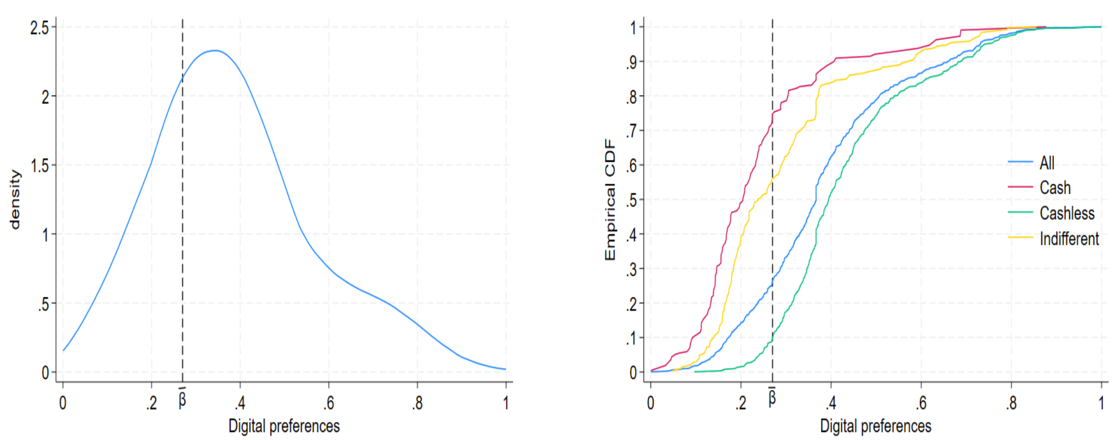
[15]See Appendix 7.1 for details on our estimation of digital preferences using SPACE 2022 wave.

[16]This approach has also been used to evaluate indicators of economic recessions and expansions (Berge and Jordà (2011)), to evaluate alternative policy settings of borrower-based instruments (Giordana and Ziegelmeyer (2024)), and to evaluate crises early-warning systems (Drehmann and Juselius (2014); Candelon et al. (2012); Detken et al. (2014)).

[17]See Appendix 7.2 for details on our implementation of the signals approach.

function (CDF) of the digital preferences measure, both for the whole sample and separately by stated payment preference. The CDF is farthest right among those who preferred cashless payments (green line). Thus, the distribution among this group stochastically dominates the other CDFs (including the whole sample CDF - blue line), confirming that our digital preferences measure is useful to identify the stated preference among payment methods. The estimated threshold $\hat{\hat{\beta}}$ from the signals approach is indicated by a dotted vertical line in both Figure 4a and Figure 4b. From Figure 4b, around 10% of those who stated they prefer cashless payments (green CDF) are wrongly classified, as are 25% of those who stated they prefer cash payments (red CDF). However, our focus is on those who stated they were indifferent (yellow CDF), of which 45% are assigned to cashless payments and 55% to cash payments, which seems reasonable.

Figure 4: Digital preferences density and CDF by stated preference



(a) Digital preferences density (b) CDF by stated payment preferences

Source: Own calculations using SPACE 2022 wave for Luxembourg; weighted results. Vertical lines indicate estimated threshold $\hat{\hat{\beta}}$ separating cash-preferring from cashless-preferring consumers.

To distinguish consumer types, we consider their stated preferences for payment methods, their estimated digital preferences and their reported payment behaviour. Consumers who stated they prefer cash payments are assigned to the *cash-only* type if they reported zero cashless payments and to the *cash-preferring* type otherwise. Those who stated they prefer cashless payments are assigned to the *cashless-only* type if they reported zero cash payments and to the *cashless-preferring* type otherwise. Those who reported they were indifferent are treated differently if their digital preference measure is above or below the threshold $\hat{\hat{\beta}}$.

Indifferent cases below the threshold are assigned to the *cash-only* type if they reported zero cashless payments and to the *cash-preferring* type otherwise. Finally, indifferent cases above the threshold are assigned to the *cashless-only* type if they reported zero cash payments and to the *cashless-preferring* type otherwise. Figure 3b illustrates the resulting shares of consumer types among adults resident in Luxembourg in 2022. Only 1% are *cash-only*, while 22% are *cash-preferring* although they also use cashless payments. Among the remaining 77%, 49% are *cashless-only*, while 28% are *cashless-preferring*, although they also use cash.

Table 1: Value of annual payments by consumer type and instrument (thousand euro)

Type		**Cash**	**Cashless**	**Debit/credit cards**	**Other**	**Total**
Cash-only	*Mean*	20,352	0	0	771	21,123
	Median	1,642	0	0	0	2,748
	Min.	0	0	0	0	0
	Total	104,589	0	0	3,963	108,552
Cash-preferring	*Mean*	18,052	29,463	17,760	121	47,636
	Median	6,734	15,199	0	0	32,320
	Min.	0	12	0	0	294
	Total	2,003,448	3,269,816	1,971,018	13,434	5,286,698
Cashless-only	*Mean*	0	44,896	31,041	173	45,070
	Median	0	27,771	12,045	0	27,932
	Min.	0	0	0	0	0
	Total	0	11,411,252	7,889,767	44,021	11,455,273
Cashless-preferring	*Mean*	16,292	44,002	32,080	30	60,324
	Median	7,300	26,688	14,033	0	43,195
	Min.	2	0	0	0	362
	Total	2,335,470	6,307,537	4,598,619	4,306	8,647,313
Overall	*Mean*	8,651	40,863	28,151,	128	49,642
	Median	0	24,240	8,760	0	33,600
	Min.	0	0	0	0	0
	Total	4,443,507	20,988,605	14,459,404	65,725	25,497,837

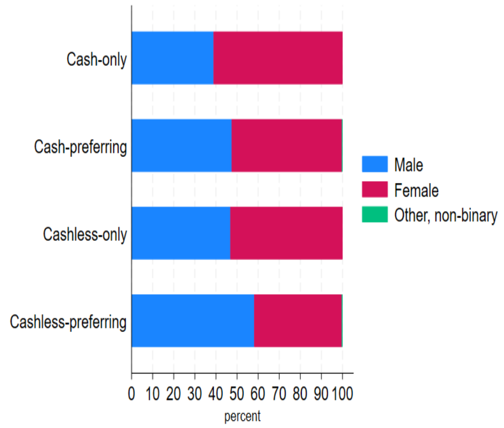
Source: Own calculations using SPACE 2022 wave for Luxembourg; weighted results. Payments at point of sale and online (including regular payments). Cashless payment methods include debit/credit card, mobile, Paypal (and other apps), direct debit, bank transfers, crypto and fidelity points. Other payment methods include *cheque* and *other*.

Table 1 breaks down the annual amount paid by consumer type and payment instrument. *Cash-only* consumers represent only 0.4% of the value of all payments over a year with a median value of 1,642 thousand euro paid over a year. *Cash-preferring* consumers represent 20.7% of the value of all payments over a year, of which just above one third is in cash. For this group, the median value is 6,734 thousand euro of cash payments over a year and 15,199 thousand euro of cashless payments with 60% of the value of cashless payments made using credit/debit cards (cashless payments also include direct debits, direct deposits and bank transfers). *Cashless-only* consumers represent 44.9% of the value of all payments over the year (of which 69% by credit/debit card) with their median value reaching 27,932 thousand euro paid over the year. *Cashless-preferring* consumers represent 33.9% of the value of all payments over a year with 73% being cashless payments (of which 73% by card) and a median value of 43,195 thousand euro paid over the year.

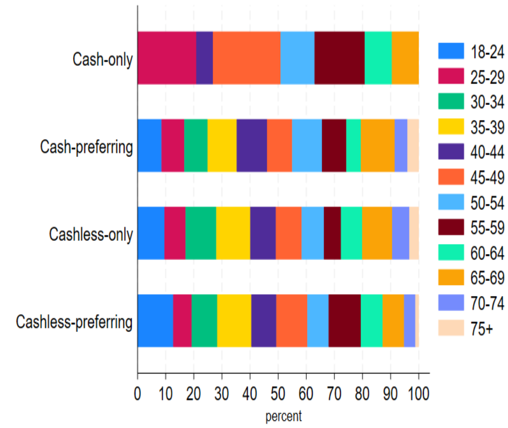
Finally, Figure 5 depicts the demographic characteristics of each type of consumer. Overall, the *cash-only* consumer type shows several specificities. Figure 5a shows more women of the *cash-only* type and more men for the *cashless-preferring* type, while the other two types are split quite evenly between men and women. Figure 9b shows that all age categories are present in each consumer type except *cash-only*, where individuals aged 75 and over do not appear. This surprising result may reflect the limited sample size (just over 1,000 individuals) or lower cash use among those in long-term care. However, those younger than 45 represent less than 30% of the *cash-only* group, compared to 50% of the other groups. The share of consumers living in rural areas is surprisingly high and may involve misreporting[18]. In any case, the share of rural dwellers does not significantly differ across consumer types (Figure 5c). Figure 5d shows only little differences in educational attainment across consumer types. The share of respondents not participating in the labour force is highest among *cash-only* consumers and the lowest among *cashless-preferring* (Figure 5e). The share of retired individuals tends to be similar across types although it is noticeably smaller among *cashless-preferring* consumers (Figure 5f).

[18]According to Eurostat, in 2023 only 32.6% of the population was rural, with 48.6% living in towns or suburbs and the remaining 18.8% in urban centers.

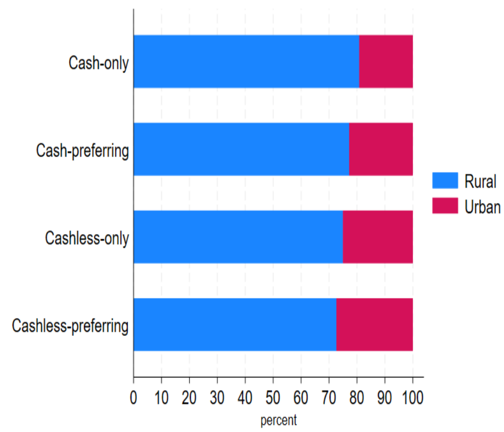
Figure 5: Socio-economic and demographic characteristics by consumer types



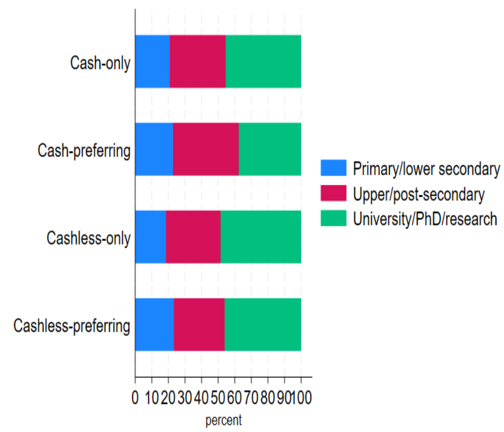
(a) Gender



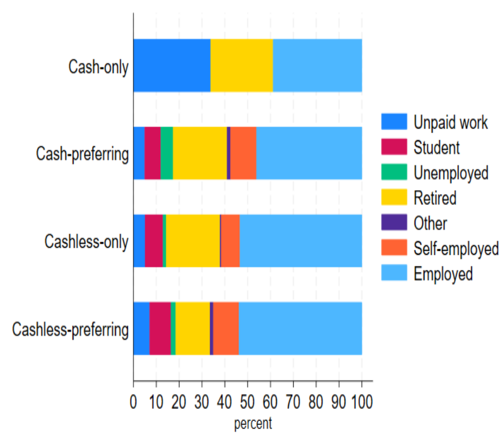
(b) Age categories



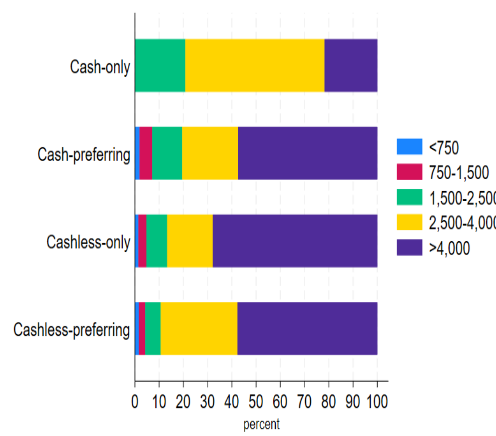
(c) Rural/urban area of residence



(d) Educational attainment



(e) Activity/inactivity status*



(f) Household monthly net income (euro)

Source: Own calculations using SPACE 2022 wave for Luxembourg; weighted results. *Unpaid work refers essentially to housekeeping activities; student category only includes full-time students; retired category includes retired and those unable to work through illness; other category is not defined in the SPACE questionnaire.

4.2 CBDC adoption under different scenarios

Based on the theoretical framework described in section 3, we estimate CBDC take-up for each individual as a share of their total annual payments. The SPACE data indicates the average amount of daily payments for different individuals, which we use to derive the value of their weekly, monthly and annual payments. In our theoretical framework, ϕ^e denotes the share of income that can only be spent using credit cards, which corresponds to the share of credit card payments of *cashless-only*, *cashless-preferring* and *cash-preferring* consumers. However, SPACE does not distinguish payments by credit card from those by debit card. Using data from the BCL *Collecte Directe des Données de Paiements* (CDDP), we estimate that credit cards accounted for 52% of the value of all transactions using cards processed by payment service providers in 2022.[19] Using this value for ϕ^e, our theoretical model predicts that *cashless-only* and *cash-preferring* consumers would not switch to CBDC unless the latter provides access to credit (through the reverse waterfall or the automatic top up of a CBDC wallet).

We consider two scenarios: (i) debit waterfall (DW), and (ii) credit waterfall (CW). In the first, CBDC payments in excess of the holding limit or of the CBDC wallet balance can only be funded from a bank deposit. In the second scenario, CBDC payments in excess of the holding limit or of the CBDC wallet balance can also be funded by credit (e.g. credit card or credit line). We consider three possible values for the holding limit on CBDC wallets: 3,000, 5,000 and 10,000 euros.

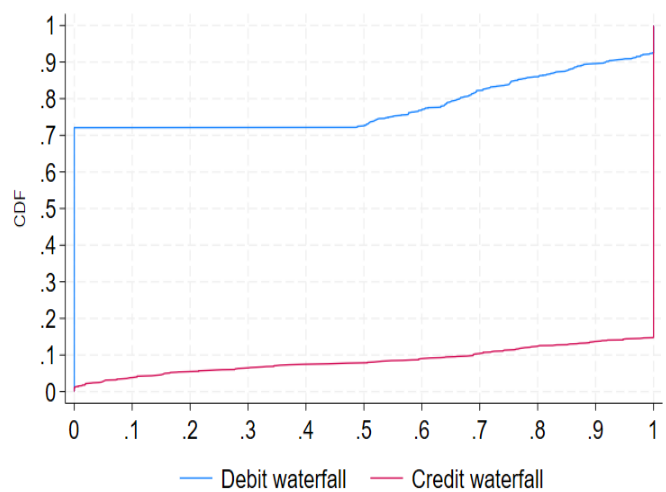
4.2.1 CBDC take-up

For each scenario, Figure 6 plots the cumulative distribution function of CBDC take-up as a share of value of point-of-sale or online payments over a year. The horizontal axis is the CBDC share of the total value of annual payments and the vertical axis is the share of the consumer population. The discontinuities are a function of the different consumer types and their respective shares of cash and cashless payments. In the debit waterfall scenario (blue line), 72% of consumers do not use CBDC at all (vertical axis) and only *cashless-preferring*

[19] To calculate this share in 2022, we divided the total value of payments using credit card and delayed debit cards by the total value of payments using all type of cards.

consumers (28% in Figure 3a) switch to CBDC, using it to cover more than 55% of the annual value of their point-of-sale or online payments (horizontal axis, blue line starts growing). In the credit waterfall scenario (red line), more than 85% of consumers (including some *cash-preferring* consumers) use CBDC to cover the entire value of their annual point-of-sale or online payments.

Figure 6: Cumulative distribution function of CBDC take-up under alternative scenarios

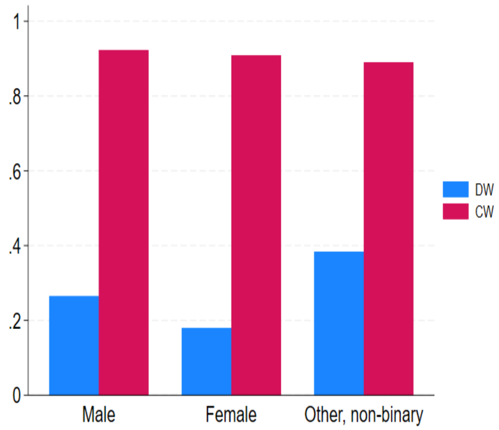


Source: Own calculations using SPACE 2022 wave for Luxembourg; weighted results. The horizontal axis is the CBDC share of the total value of annual payments. The vertical axis is the population share.

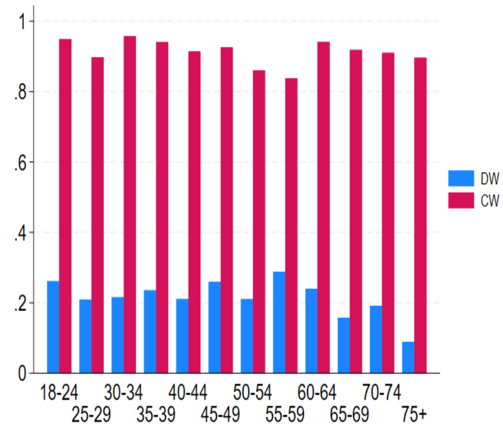
On average, CBDC accounts for 0.23 of the value of payments in the debit scenario and 0.91 in the credit waterfall scenario. Considering average CBDC take-up by socio-economic and demographic characteristics, Figure 7 shows no substantial differences across subgroups in either scenario with few exceptions.

Figure 7a reveals different average CBDC take-up by gender in the debit waterfall scenario and Figure 7b a lower average for the oldest individuals in the same scenario. In Luxembourg, women and individuals above the age of 75 feature lower CBDC take-up in the debit waterfall scenario. Take-up differences across socio-economic and demographic characteristics vanish in the credit waterfall scenario. Overall, we conclude that no specific population sub-group will be driving CBDC adoption in Luxembourg and that design characteristics will be crucial.

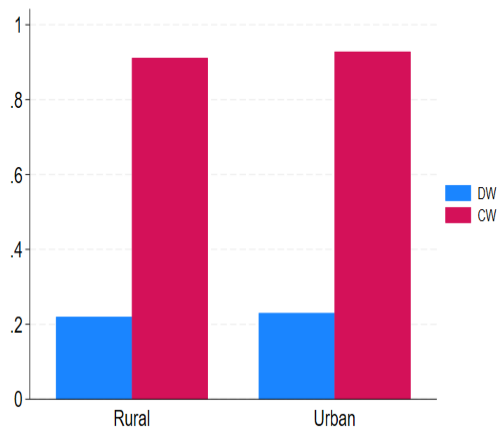
Figure 7: Average CBDC take-up by socio-economic and demographic characteristics



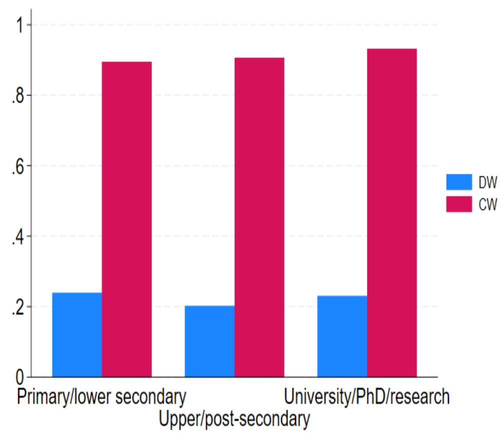
(a) Gender



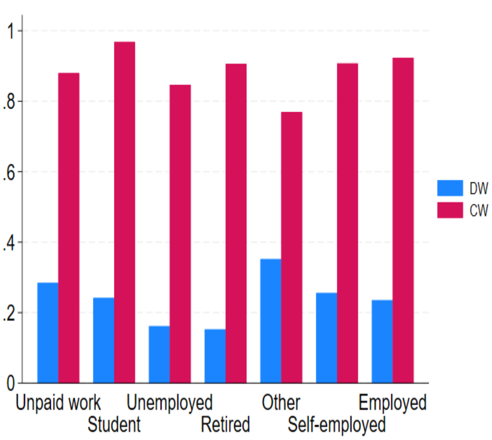
(b) Age categories



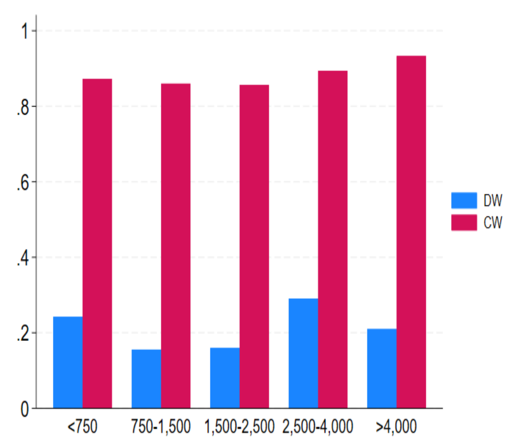
(c) Rural/urban area of residence



(d) Educational attainment



(e) Activity/inactivity status*



(f) Household monthly net income (euro)

Source: Own calculations using SPACE 2022 wave for Luxembourg; weighted results. DW: debit waterfall; CW: credit waterfall. *Unpaid work refers essentially to housekeeping activities; student category only includes full-time students; retired category includes retired and those unable to work through illness; other category is not defined in the SPACE questionnaire.

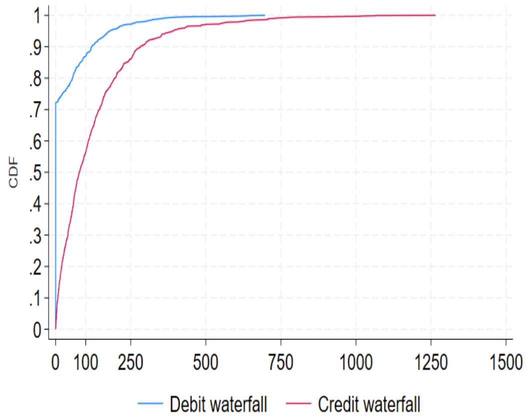
4.2.2 Impact of holding limits

The holding limit would constrain the amount of CBDC that could be stored in a wallet. However, CBDC payments are just a flow out of the wallet. Consumers wishing to use CBDC to pay more than the holding limit would need to refill their CBDC wallets as they empty. As argued in section 3.2, whether this is done manually or automatically through a reverse waterfall, CBDC wallet refilling may entail costs discouraging CBDC adoption (Result 3.3). The more frequent the CBDC wallets would empty the more convenient an automatic refill would be.

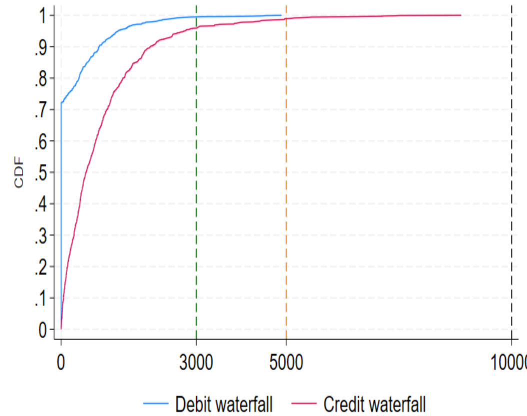
Since SPACE provides individual data on payments per day, we can cumulate daily payments to obtain payments per week, month or year. Multiplying the individual's desired CBDC share by the reported value of payments over a day, week, month or year yields an estimate of individual demand for CBDC payments at different frequencies. To identify the potential advantages of reverse waterfall mechanisms, Figure 8 plots the cumulative distribution function of estimated CBDC payments with the vertical dashed lines indicating three potential holding limits (i.e. 3, 5 and 10 thousand euro). In either scenario, no consumers would breach any of the holding limits at daily frequency (see Figure 8a). In the debit waterfall scenario, less than 1% of consumers would breach the 3,000 euro holding limit once a week and 0.05% would breach the 5,000 euro holding limit once per week (Figure 8b). In the credit waterfall scenario, 4% would breach the lower limit at least once per week, 1% would breach the intermediate limit at least once a week and none would breach the top limit (Figure 8b). At monthly frequency, all three holding limits would be breached in both scenarios with a substantial share of consumers needing to refill their wallet more than once per month (Figure 8c). In the credit waterfall scenario, 20% of consumers would breach the lowest limit, 25% would breach the intermediate limit and 7% would breach the highest limit (red line, Figure 8c). Among those breaching the highest limit, several would breach the lowest limit more than three times per month and the intermediate limit more than twice per month. Therefore, if breaching the limits is costly, a seamless credit waterfall could benefit a substantial share of consumers.

To identify the subgroups most affected by holding limits, Figure 9 plots mean CBDC

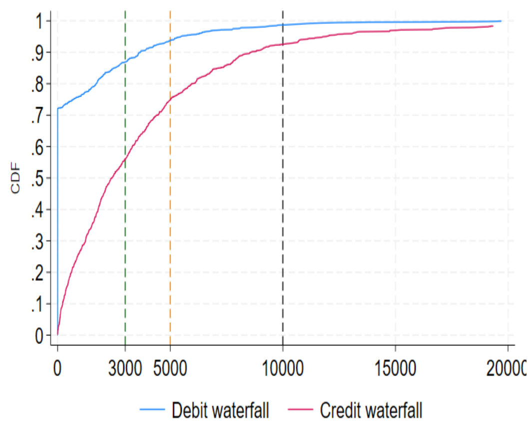
Figure 8: Cumulative distribution function of CBDC payments at different frequencies



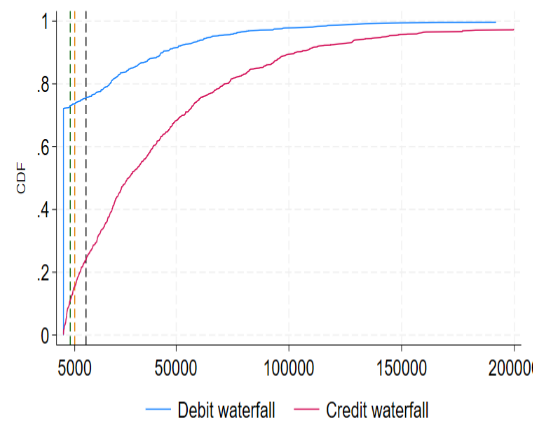
(a) Daily CBDC demand in euro



(b) Weekly CBDC demand in euro



(c) Monthly CBDC demand in euro



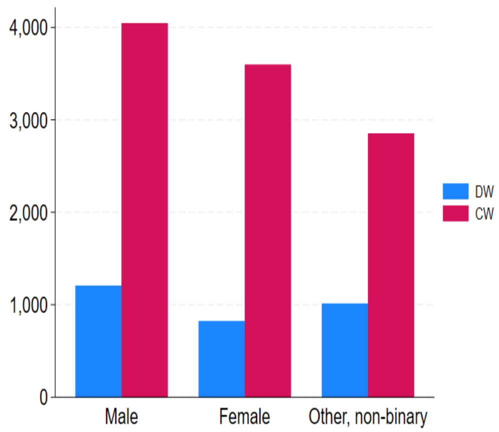
(d) Annual CBDC demand in euro

Source: Own calculations using SPACE 2022 wave for Luxembourg; weighted results. The x-axis is denominated in 2022 euro.

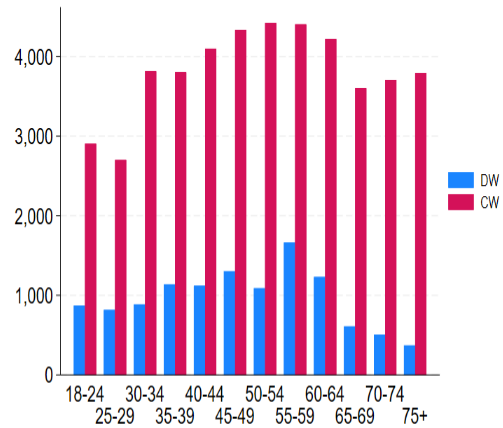
payments by socio-economic and demographic characteristics. In the debit waterfall scenario, average monthly CBDC payments rarely approach 2,000 euro. In the credit waterfall scenario, almost every population subgroup is characterized by average monthly payments above the 3,000 euro limit except for some of the younger age categories (Figure 9b), students (Figure 9e) and those in the bottom income category (Figure 9f).

The introduction of a CBDC is likely to affect demand for bank deposits and could hamper the implementation of monetary policy (Fegatelli (2022), Fegatelli (2024), Fegatelli et al. (2025)). Our framework can evaluate the share of payments that consumers in Luxembourg

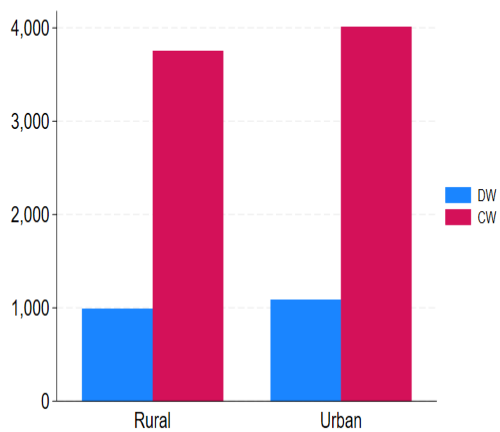
Figure 9: Average CBDC monthly payments by socio-economic and demographic characteristics



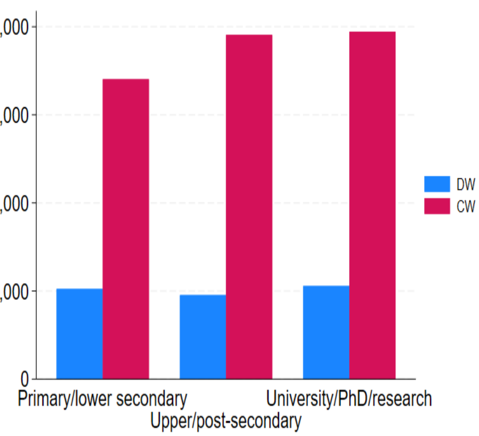
(a) Gender



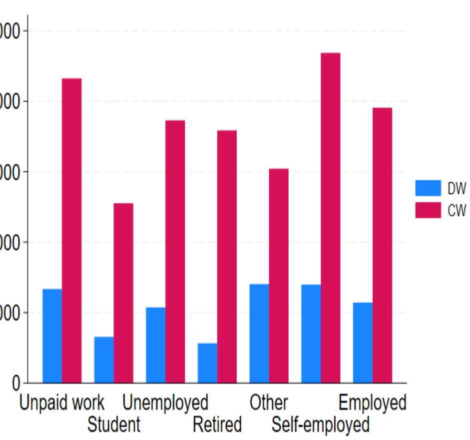
(b) Age categories



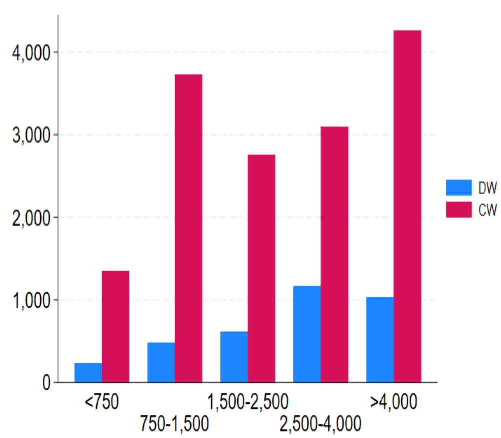
(c) Rural/urban area of residence



(d) Educational attainment



(e) Activity/inactivity status*



(f) Household monthly net income (euro)

Source: Own calculations using SPACE 2022 wave for Luxembourg; weighted results. DW: debit waterfall; CW: credit waterfall. *Unpaid work refers essentially to housekeeping activities; student category only includes full-time students; retired category includes retired and those unable to work through illness; other category is not defined in the SPACE questionnaire.

would execute in CBDC. We sum CBDC monthly payments in the debit waterfall and credit waterfall scenarios assuming either no holding limit or a 3,000 euro holding limit, in which case we distinguish two levels of CBDC adoption (low and mild). For "low" CBDC adoption, we only consider those consumers whose CBDC total monthly payments would be below the holding limit. This assumes that consumers for whom the value of desired CBDC payments over a month would exceed the holding limit decide not to adopt the CBDC. Instead, for "mild" CBDC adoption, we also consider consumers whose desired CBDC monthly payments would exceed the holding limit, but we assume that they cannot afford to refill the CBDC wallet in the given month so that their CBDC monthly payments would be bounded by the holding limit.[20]

Table 2 shows the results. The aggregate outcome is consistent with the results above, with CBDC adoption being substantially higher when CBDC credit is allowed.

Table 2: Aggregate CBDC take-up by scenario, holding limit and adoption level (total value in million euro and share of monthly payments)

Holding limit	**Adoption level**	**Scenarios**	
		Debit waterfall	Credit waterfall
No limit		521.3 *(24%)*	1,948.8 *(92%)*
€3,000	Mild	319.9 *(15%)*	1,009.7 *(48%)*
	Low	118.4 *(5%)*	336.2 *(16%)*

Source: Own calculations using SPACE 2022; weighted results in million euro and share in value of total monthly payments in parentheses.

CBDC adoption is naturally highest when there is no holding limit (first row in Table 2), reaching 24% of the value of total monthly payments in the debit scenario and 92% in the credit scenario. Under low CBDC adoption, consumers whose CBDC payments would exceed the 3,000 euro holding limit do not adopt CBDC, so that total CBDC payments only represent 5% of the value of all monthly payments in the debit scenario and 16% in the credit scenario (low adoption row in Table 2). Instead, under mild adoption, all consumers breaching the holding limit also use CBDC payments but only up to the limit (they do not refill their wallet). In this case, CBDC take-up would reach 15% of the value of all monthly payments in the debit scenario and 48% in the credit scenario. If the refilling was too costly

[20]This reflects a consumer choice that builds on our theoretical Result 3.3. However, it could also result from a policy choice if the total value of CBDC payments per month was deliberately limited.

or too inconvenient, or if the holding limit was imposed on the flow of CBDC payments rather than the stock, then CBDC take-up would fall between the low and the mild values. Of course, if CBDC wallets can be refilled cheaply and easily, then CBDC take-up would fall between the mild and the no limit case, depending on the cost to users of refilling their CBDC wallet.

Aggregate figures in Table 2 (million euro) could be used to study the impact on Luxembourg banks from the introduction of a CBDC. However, such an analysis would be subject to two caveats. First, our results slightly overestimate the impact on banks as SPACE data includes cash payments, some of which do not transit through payment accounts with banks. Second, our estimates focus on the transactional motive for CBDC adoption and ignore use as a store of value. Therefore, our results underestimate CBDC demand in situations where the solvency of some banks or the operation of the deposit insurance scheme is challenged. In addition, any softening of the assumption that CBDC bears zero interest could encourage demand for the CBDC as a store of value.

5 Conclusion

To estimate consumer CBDC adoption for payments, we implemented a micro-simulation based on a theoretical model of consumer choice among payment methods. Simulations are calibrated to 2022 data for Luxembourg from the Study on the payment attitudes of consumers in the euro area (SPACE).

Results suggest that the level of CBDC adoption would depend critically on the design chosen. In particular, CBDC adoption would be significantly higher if it is linked to sources of consumer credit, making CBDC more widely accepted than card payments at an equivalent cost and with similar convenience. Under these conditions, a substantial share of consumers may switch to CBDC payments, pushing their monthly value beyond several potential holding limits. Micro-data analysis suggests that CBDC take-up would not vary significantly across individuals by socio-economic or demographic characteristics. However, CBDC non-adopters, consumers with strong preferences for cash payments, tend to be older, with no formal employment or retired, and are mainly in the middle of the income distribution.

We plan three extensions. First, we intend to apply our methodology to other euro area countries using the 2024 SPACE survey. Second, we plan to compare consumers' behaviour during the pandemic to that in the 2024 SPACE survey. Finally, we plan to extend the theoretical model to consider precautionary demand for CBDC.

6 Mathematical appendix

6.1 Proof of result 3.1

For parsimony of payment method choice, we assumed a linear utility function (1). Therefore, consumer i prefers cashless payments if $\beta_i > 0.5$, cash payments if $\beta_i < 0.5$, and is indifferent if $\beta_i = 0.5$. However, independently of β_i, a consumer i may still pay using a not preferred method depending on the values of the parameters ρ, ϕ_i^e, α_i and D. In addition, given our assumption that merchants cannot pass through transactions fees to consumers using cashless methods, indifference between cashless and cash payments requires that their marginal rate of substitution equals ρ for each consumer i:

$$\frac{\beta_i}{1-\beta_i} = \rho \tag{11}$$

As $\rho \in [0, 1]$, (11) implies that independently of ρ consumer i is of cashless type if $\beta_i > 0.5$. Moreover, consumer i is of cash-only type if $\beta_i \leq \frac{\rho}{(1+\rho)}$. However, a cash-lover or indifferent consumer would also use cashless methods if $\frac{\rho}{(1+\rho)} < \beta_i \leq 0.5$. In addition, consumers who using cashless payments need sufficient expected cash income to pay for the lump-sum fee: $[y_i (1 - \phi_i^e) - D] \geq 0$.

Taking into account the share of available cash (i.e. cash-income), cash-only consumers may have to pay cashless if:

$$\underbrace{y_i (1-\phi_i^e)\,\rho\,(1-\beta_i)}_{\text{Cash-only utility}} < \underbrace{[y_i (1-\phi_i^e) - D]\,\rho\,(1-\beta_i) + y_i\phi_i^e\beta_i}_{\text{Cash-preferring utility}}$$

$$\frac{\rho}{\frac{y_i\phi_i^e}{D} + \rho} < \beta_i \tag{12}$$

Therefore, a cash-preferring consumer is characterized by:

$$D \leq y_i\left(1-\phi_i^e\right) \text{ and} \tag{13}$$

$$\frac{\rho}{\frac{y_i\phi_i^e}{D}+\rho} < 0.5 \text{ if } 0 < \phi_i^e \leq 1 \text{ or} \tag{14}$$

$$\frac{\rho}{1+\rho} < \beta_i \leq 0.5 \text{ if } \phi_i^e = 0. \tag{15}$$

A cashless consumer would pay cash if cashless methods are too expensive $D > y_i\left(1-\phi_i^e\right)$ or, if $D < y_i\left(1-\phi_i^e\right)$ and $\alpha_i < 1$:

$$\underbrace{\beta_i y_i \phi_i^e + \alpha_i\left[y_i\left(1-\phi_i^e\right)-D\right]}_{\text{Cashless-only utility}} < \beta_i y_i \phi_i^e + \alpha_i\left[y_i\left(1-\phi_i^e\right)-D\right]+$$

$$\underbrace{+\left(1-\beta_i\right)\left[y_i\left(1-\phi_i^e\right)-D\right]\rho\left(1-\alpha_i\right)}_{\text{Cashless-preferring utility}} \tag{16}$$

$$0 < \left(1-\beta_i\right)\left[y_i\left(1-\phi_i^e\right)-D\right]\rho\left(1-\alpha_i\right) \tag{17}$$

6.2 Proof of result 3.2

We assumed that the CBDC does not allow a reverse waterfall mechanism funded with credit. Therefore, the CBDC does not represent an alternative to credit card payments.

Substitution occurs if welfare benefits surpass losses for each consumer i:

1. **Cash-for-CBDC**

$$\text{Benefits: } \left(1-\alpha_i\right)\left[\left(1-\phi_i^e\right)y_i - D - D_{CBDC}\right]\left[\beta_i - \rho\left(1-\beta_i\right)\right]$$

$$\text{Losses: } > D_{CBDC}\left[\left(1-\alpha_i\right)\left(1-\beta_i\right)\rho + \alpha_i\beta_i\right] \tag{18}$$

$$\alpha_i < 1 - \frac{\beta_i}{\left(1-\beta_i\right)\left[\frac{\beta_i}{\left(1-\beta_i\right)}-\rho\right]} \cdot \frac{D_{CBDC}}{\left[\left(1-\phi_i^e\right)y_i - D\right]} \tag{19}$$

From (19), net benefits are positive if α_i is sufficiently low, that is the case for consumers of the cashless type only, otherwise the first factor of the second term in the right-hand-side would be negative, potentially leading to $\alpha_i > 1$, which is undefined. In addition, as the first factor of the second term in the right-hand-side is higher than one, the second factor should be lower than one, otherwise α_i could be negative, which is undefined. This condition is satisfied if $\phi^e < 1 - \frac{D+D_{CBDC}}{y}$ as in (2), (5) and (6). Therefore, only consumers with enough cash resources left (numerator of the second factor of the right-hand-side lower than the denominator) would benefit from converting cash into CBDC.

2. **Debit-card-for-CBDC** substitution concerns constrained-cashless consumers and it occurs if conditions in item 1 are satisfied. In fact, because of the parsimony assumption, constrained-cashless consumers that switched from cash to CBDC would therefore prefer using CBDC and credit cards to using CBDC, debit cards and credit cards.

3. **Credit-card-for-CBDC** Cashless and constrained cashless consumers with sufficiently low late expected income would prefer to abandon credit cards if:

$$\text{Benefits:}\,(D - D_{CBDC})\,\beta_i$$
$$\text{Losses:}\, > y_i\phi_i^e\beta_i$$
$$\phi_i^e < \frac{D - D_{CBDC}}{y_i} \tag{20}$$

As CBDC is assumed to work as a debit card with legal tender, condition (20) implies that these consumers totally switch to CBDC inducing additional demand than the credit-card-for-CBDC substitution effect alone.

7 Statistical appendix

7.1 Digital preference estimation using SPACE

We selected a set of indicators from SPACE 2022 wave (definitions in Table 3). We then used exploratory factor analysis (EFA) to assess whether the selected indicators could contribute to estimating a latent a factor that represents individual digital preferences.

First, we evaluated whether there was sufficient correlation to perform factor analysis. The Bartlett test of sphericity rejects the null hypothesis that the correlation matrix is the identity matrix (variables are orthogonal). In addition, the Kaiser-Meyer-Olkin measure was

Table 3: Indicators for measuring latent digital preferences: definitions and factor loadings

Indicator Label	Type	Definition	Loading
l_1	Binary	1 if respondent has land-line phone in the household	0.1272
l_2	Binary	1 if respondent has a mobile phone	0.0603
l_3	Binary	1 if respondent has access to online banking	0.0832
l_4	Binary	1 if respondent paid online	0.8281
l_5	Ordered	Number of online purchases	0.9163
l_6	Binary	1 if respondent paid online for buying clothes and sportwear	0.3971
l_7	Binary	1 if respondent paid online for buying food and daily supplies	0.5421
l_8	Binary	1 if respondent paid online for buying medicine, comsmetics and drugstore products	0.3445
l_9	Binary	1 if respondent paid online for charitable donations	0.1669
l_{10}	Binary	1 if respondent paid online for buying luxury goods	0.2108
l_{11}	Binary	1 if respondent prefers paying with card or other cashless methods	0.1913
l_{12}	Binary	1 if respondent prefers mobile payments (including wearables like smartwatches)	0.1967
l_{13}	Binary	1 if respondent reports that cash has no advantages compared with card payments	0.0481
l_{14}	Binary	1 if respondent reports that having the option of using cash is not so important or not important at all	0.1401
l_{15}	Binary	1 if respondent has crypto-assets also known as cryptocurrency or virtual assets (e.g. Bitcoin, Ethereum)	0.1214
l_{16}	Binary	1 if respondent reports that transaction speed is one of the three most important advantages of card payments compared with cash	0.0539
l_{17}	Binary	1 if respondent reports that ease of use is one of the three most important advantages of card payments compared with cash	0.0534
l_{18}	Binary	1 if respondent reports that logistical burden is one of the three most important advantages of card payments compared with cash	0.0504

0.612, above the conventional threshold required for the sample to be "adequate" for factor analysis.

Second, we performed a principal factor analysis, which identified a single factor with eigenvalue higher than 1 that explains 70% of the common variance. The last column of Table 3 reports the factor loadings. We refer to this factor as "digital preferences".

Third, we evaluated the reliability (or internal consistency) of the latent variable measurement using Cronbach's alpha. Table 4 reports the item-test correlation, item-rest correlation and Cronbach's alpha when excluding the item in the row. Item-rest correlation may be more adequate to detect poorly fitting items than item-test correlation because the scale may be distorted by the presence of weak items. In the last row, Cronbach's alpha is above 0.58, which is not very high, but still suggests this set of indicators could provide a reliable measure of the latent factor. Indicator l_2 has the lowest item-rest correlation and dropping it slightly improves Cronbach's alpha (see last column). Indicators l_4 and l_5 provides the same information, thus only one of them should be kept. We decided to keep l_5 and drop l_4 because it facilitates the convergence of the Confirmatory Factor Analysis (CFA) model. Cronbach's alpha then falls to 0.5 indicating a weak reliability of the measure.

The latent variable model has 18 equations including a total of 400 coefficients plus a variance-covariance matrix to be estimated by minimising the difference between the observed and predicted variance-covariance matrix across observed variables. We adopt the default identification assumptions in the Stata software. We proceed in steps, first estimating a constrained version of the model and then using the results as initial values to estimate the next "less" constrained version of the model. Stata software does not provide goodness-of-fit measures for such a generalized linear models.

Table 5 reports the Confirmatory Factor Analysis outcome of our preferred model, which involves estimating the coefficients on socio-economic indicators as well as the pattern coefficients λ that measure the effect on the indicators of the unobservable factor. Among the indicators, $l_{16} - l_{18}$ represent characteristics of payment methods that were reported as advantages of cashless payments over cash: transaction speed, ease of use and logistical burden (see Table 3 for definitions). At the bottom of Table 5, the pattern coefficients are positive and statistically significant, indicating that digital preference factor influences these percep-

Table 4: Internal consistency measures

Indicator	Item-test correlation	item-rest correlation	Alpha
l_1	0.2842	0.1405	0.576
l_2	0.1007	0.053	0.5819
l_3	0.2722	0.1282	0.5778
l_4	0.665	0.551	0.503
l_5	0.6936	0.4386	0.5096
l_6	0.3245	0.2459	0.5669
l_7	0.5098	0.4226	0.5442
l_8	0.2867	0.2242	0.5711
l_9	0.1754	0.1411	0.5789
l_{10}	0.1673	0.1371	0.5795
l_{11}	0.5196	0.2962	0.5494
l_{12}	0.3471	0.237	0.5639
l_{13}	0.1827	0.0938	0.5796
l_{14}	0.4382	0.2703	0.5545
l_{15}	0.2195	0.1165	0.5777
l_{16}	0.2621	0.0808	0.5893
l_{17}	0.2822	0.1	0.5861
l_{18}	0.2963	0.1208	0.5817
Cronbach's alpha			0.581

tions. Other characteristics including security, merchant acceptance or budget awareness do not load the factor but were considered as exogenous determinants of l_{11} (i.e. preference for cashless payments).

Table 5: Confirmatory Factor Analysis: Estimated coefficients on socio-economic variables and digital preferences

	l_1	l_3	l_5	l_6	l_7	l_{11}	l_{12}	l_{13}	l_{14}	l_{15}	l_{16}	l_{17}	l_{18}
Gender	-0.062***	0.027***	0.164***	-0.482***	0.461***	0.031***	0.086***	-0.309***	-0.266***	0.597***	0.004	-0.027***	-0.113***
	(0.004)	(0.004)	(0.006)	(0.015)	(0.014)	(0.004)	(0.010)	(0.012)	(0.004)	(0.011)	(0.004)	(0.004)	(0.004)
Age													
2	0.757***	0.492***	-0.377***	-0.591***	0.327***	-0.405***	0.293***	1.857***	-0.287***	0.358***	0.399***	-0.603***	0.525***
	(0.014)	(0.013)	(0.016)	(0.036)	(0.042)	(0.013)	(0.024)	(0.042)	(0.012)	(0.029)	(0.012)	(0.012)	(0.012)
3	0.324***	0.153***	-0.573***	-0.679***	0.178***	-0.148***	-0.078***	1.896***	0.254***	0.270***	0.541***	-0.401***	0.443***
	(0.013)	(0.013)	(0.017)	(0.036)	(0.043)	(0.014)	(0.026)	(0.049)	(0.013)	(0.030)	(0.012)	(0.013)	(0.012)
4	0.084***	0.316***	-0.478***	-0.773***	0.130***	-0.241***	0.349***	2.191***	-0.265***	0.067**	0.465***	-0.850***	0.314***
	(0.013)	(0.013)	(0.016)	(0.036)	(0.043)	(0.013)	(0.025)	(0.047)	(0.012)	(0.030)	(0.012)	(0.012)	(0.012)
5	0.349***	0.201***	-0.205***	-1.858***	-0.037	-0.303***	-0.812***	2.014***	-0.449***	-0.020	0.376***	-0.799***	0.519***
	(0.013)	(0.013)	(0.016)	(0.042)	(0.044)	(0.014)	(0.028)	(0.047)	(0.013)	(0.030)	(0.012)	(0.012)	(0.012)
6	-0.037***	0.145***	-0.735***	-1.525***	-0.232***	-0.378***	-0.613***	1.982***	-0.206***	-1.694***	0.464***	-0.696***	0.439***
	(0.013)	(0.013)	(0.017)	(0.041)	(0.046)	(0.014)	(0.028)	(0.049)	(0.013)	(0.040)	(0.012)	(0.012)	(0.012)
7	0.363***	0.014	-0.998***	-1.242***	-1.073***	-0.703***	-1.346***	2.874***	-0.296***	-1.023***	0.035***	-0.923***	0.309***
	(0.014)	(0.013)	(0.018)	(0.041)	(0.050)	(0.014)	(0.034)	(0.047)	(0.013)	(0.037)	(0.013)	(0.013)	(0.012)
8	0.224***	0.491***	-0.891***	-0.928***	-1.044***	-0.390***	-0.487***	2.117***	-0.354***	-0.578***	-0.103***	-0.705***	0.467***
	(0.014)	(0.014)	(0.018)	(0.041)	(0.048)	(0.014)	(0.028)	(0.050)	(0.013)	(0.034)	(0.013)	(0.013)	(0.012)
9	0.544***	0.432***	-0.151***	-0.697***	-0.752***	-0.454***	-1.081***	3.253***	0.062***	-0.259***	-0.189***	-0.806***	0.554***
	(0.015)	(0.014)	(0.018)	(0.044)	(0.049)	(0.015)	(0.035)	(0.048)	(0.014)	(0.035)	(0.014)	(0.013)	(0.013)
10	-0.046***	0.130***	-1.011***	-1.865***	-1.753***	-0.325***	-1.257***	2.717***	-0.110***	-1.561***	-0.181***	-0.960***	0.274***
	(0.015)	(0.015)	(0.020)	(0.058)	(0.055)	(0.015)	(0.037)	(0.051)	(0.014)	(0.050)	(0.014)	(0.014)	(0.014)
11	0.350***	0.267***	-0.449***	-1.020***	-1.236***	-0.206***	-1.875***	2.859***	0.202***	-38.610	-0.097***	-0.809***	0.415***
	(0.017)	(0.016)	(0.021)	(0.058)	(0.057)	(0.017)	(0.047)	(0.053)	(0.016)	(5106317.133)	(0.015)	(0.015)	(0.015)
12	0.822***	-0.177***	-1.209***	-3.326***	-0.365***	-0.422***	-2.170***	-35.288	0.035**	0.006	0.305***	-0.876***	-0.356***
	(0.022)	(0.017)	(0.025)	(0.076)	(0.058)	(0.019)	(0.064)	(5075255.095)	(0.018)	(0.044)	(0.016)	(0.017)	(0.017)
Household	0.015***	-0.052***	0.018***	0.086***	-0.210***	0.028***	-0.135***	-0.017***	-0.029***	-0.177***	-0.012***	-0.040***	0.013***
size	(0.002)	(0.002)	(0.003)	(0.007)	(0.006)	(0.002)	(0.004)	(0.005)	(0.002)	(0.004)	(0.002)	(0.002)	(0.002)
Education													
2	0.399***	0.012**	0.506***	0.133***	0.972***	-0.091***	1.005***	0.172***	-0.209***	-0.120***	0.201***	0.180***	0.159***
	(0.006)	(0.006)	(0.009)	(0.022)	(0.023)	(0.006)	(0.017)	(0.018)	(0.006)	(0.016)	(0.005)	(0.005)	(0.005)
3	0.248***	-0.112***	0.339***	-0.302***	0.627***	0.175***	0.545***	0.451***	-0.125***	0.014	0.303***	0.197***	0.207***
	(0.006)	(0.006)	(0.009)	(0.021)	(0.022)	(0.006)	(0.017)	(0.017)	(0.005)	(0.015)	(0.005)	(0.005)	(0.005)
Working status													
Student	0.447***	0.054***	-0.453***	-0.964***	0.119***	-0.241***	-0.092***	1.497***	-0.257***	-0.082***	0.711***	-0.588***	0.170***
	(0.013)	(0.012)	(0.017)	(0.038)	(0.043)	(0.013)	(0.024)	(0.038)	(0.012)	(0.030)	(0.012)	(0.012)	(0.012)
Unemp.	0.193***	0.004	0.029	0.622***	0.448***	-0.779***	-38.925	-37.737	-0.089***	-38.770	0.310***	0.066***	-0.316***
	(0.014)	(0.014)	(0.020)	(0.041)	(0.046)	(0.013)	(7431776.911)	(6382345.109)	(0.013)	(7303741.477)	(0.012)	(0.012)	(0.012)
Retired	0.358***	-0.109***	0.035***	-0.948***	0.935***	-0.072***	-0.083***	-0.715***	-0.462***	-0.720***	0.417***	0.101***	0.043***
	(0.010)	(0.009)	(0.012)	(0.036)	(0.030)	(0.009)	(0.024)	(0.022)	(0.008)	(0.028)	(0.008)	(0.007)	(0.008)
Monthly income													

Continued on next page

Table 5 – continued from previous page

	l_1	l_3	l_5	l_6	l_7	l_{11}	l_{12}	l_{13}	l_{14}	l_{15}	l_{16}	l_{17}	l_{18}
2	-0.415***	-0.279***	0.490***	1.214***	0.873***	0.023	-1.466***	-1.058***	-1.407***	-0.524***	0.165***	0.142***	-0.114***
	(0.020)	(0.019)	(0.029)	(0.070)	(0.085)	(0.020)	(0.038)	(0.056)	(0.020)	(0.039)	(0.018)	(0.018)	(0.018)
3	-0.603***	-0.120***	0.060**	0.085	0.215***	-0.240***	-1.563***	-0.881***	-1.090***	-1.464***	0.004	-0.159***	-0.560***
	(0.019)	(0.017)	(0.028)	(0.070)	(0.082)	(0.018)	(0.033)	(0.046)	(0.018)	(0.042)	(0.017)	(0.016)	(0.017)
4	-0.015	-0.065***	0.276***	-0.476***	2.058***	0.004	-1.201***	-1.245***	-0.937***	-0.586***	0.181***	-0.129***	-0.395***
	(0.018)	(0.017)	(0.026)	(0.067)	(0.076)	(0.018)	(0.026)	(0.043)	(0.017)	(0.032)	(0.016)	(0.015)	(0.016)
5	0.267***	0.349***	0.399***	0.592***	1.493***	0.206***	-0.939***	-0.624***	-0.613***	-0.294***	0.320***	-0.101***	0.045***
	(0.018)	(0.016)	(0.026)	(0.065)	(0.075)	(0.017)	(0.025)	(0.041)	(0.017)	(0.031)	(0.016)	(0.015)	(0.015)
Advantages of card payments													
Acceptance						-0.050***							
						(0.005)							
Security						0.520***							
						(0.005)							
Budget awareness						0.508***							
						(0.006)							
Pattern coefficients (digital preferences)													
λ	1	0.539***	4.67***	7.67***	8.891***	7.22***	7.45***	6.76***	1.336***	2.613***	1.69***	1.21***	1.53***
		(0.012)	(0.061)	(0.115)	(0.129)	(0.113)	(0.146)	(0.129)	(0.022)	(0.042)	(0.038)	(0.02)	(0.032)
Cons.	0.208***	0.673***	-1.78***	-3.66***	-6.065***	-5.01***	-6.71***	-6.15***	0.668***	-1.35***	-4.22***	1.29***	-1.51***
	(0.023)	(0.021)	(0.031)	(0.078)	(0.094)	(0.025)	(0.049)	(0.040)	(0.021)	(0.039)	(0.062)	(0.021)	(0.046)
σ_{dp}	0.074***												
	(0.002)												

continuation of Table 5

	l_8	l_9	l_{10}
Pattern coefficients (digital preferences)			
λ	7.613***	8.069***	7.254***
	(0.123)	(0.161)	(0.143)
Constant	-4.902***	-6.665***	-6.086***
	(0.024)	(0.048)	(0.039)

7.2 Signals approach to identify consumers preferring cash

We implement a grid search over possible values of our digital preferences measure to identify the "optimal" threshold that separates individuals preferring cashless payment methods from those preferring cash while minimising classification errors. This technique is known as the "signals approach" (Kaminsky et al. (1998)) or "signalling approach" (Detken et al. (2014)).

The confusion matrix in Table 6 illustrates the different possible outcomes when classifying individuals based on their digital preference measure. The two rows of the matrix correspond to the status of the signal (triggered if the digital preference measure is above the threshold, not triggered if below) and the two columns correspond to individual responses to question l_{11} (preference for cashless payments or preference for cash). The outcome of the classification depends on whether the status of the signal (in the row) matches the condition in the columns. In the first column, the individual prefers cashless payments, so a triggered signal results in an accurate "true positive" case in the top left cell. However, some individuals who report a preference for cashless payments may have a digital preference measure that does not trigger the signal, leading to a "false negative" case in the bottom left cell. In the second column, the individual reports a preference for cash payments, so if the digital preferences measure triggers the signal the result is a "false positive" case in the top right cell. The bottom right cell corresponds to individuals that report a preference for cash and whose digital preference measure does not trigger the signal, leading to an accurate classification as a "true negative" case.

Table 6: Confusion matrix and associated statistics

Signal	Condition		
	Cashless	Cash	
Triggered	True positive (TP)	False positive (FP)	
Not triggered	False negative (FN)	True negative (TN)	
Statistics	True positive rate 1-Type II error $TPR = \frac{TP}{TP+FN}$	False positive rate Type I error $FPR = \frac{FP}{FP+TN}$	Loss function = $\theta\,(1 - TPR) + (1 - \theta)\,FPR$ with $\theta \in (0, 1)$

Type I classification errors correspond to "false positive" cases in the second column. Type II errors correspond to "false negative" cases in the first column. Varying the threshold that triggers the signal will reveal a trade-off between these two types of classification errors.

For instance, higher thresholds will reduce the number of individuals triggering the signal and therefore increase type II errors. Lower thresholds will raise the number of individuals triggering the signal and therefore increase type I errors.

The signals approach relies on three elements: the binary condition variable, the criteria to evaluate the performance of different classification rules and the criteria to identify the "optimal" threshold for each rule.

a The condition variable takes the value one for individuals who prefer cashless payments and zero for those who prefer cash payments.

b To compare classification rules, we use the Receiver Operating Characteristic (ROC) curve. In particular, the Area under the ROC curve (AUROC), a statistic ranging from 0 to 1, summarises the performance of each classification rule across all possible thresholds. A classification rule with an AUROC of 1 is perfectly informative, while one with an AUROC of 0.5 is uninformative. An AUROC significantly lower than 0.5 may be informative if it indicates a systematic inverse relationship between the signal and the underlying condition. Below we analyse only one rule, based on the digital preference indicator as measured by our preferred model (see appendix 7.1).

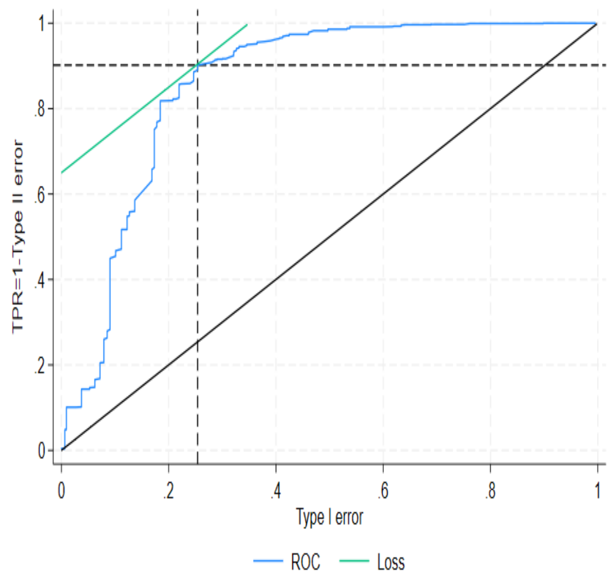
c Criteria to identify "optimal" limits

   Following Giordana and Ziegelmeyer (2024), we minimise the loss function (bottom right cell in Table 6) to find the "optimal" limit. Varying the loss function parameter θ allows one to consider different policy preferences regarding the trade-off between type I and type II errors.

Figure 10 plots the ROC curve of the classification using our digital preference indicator. The ROC curve plots type I and type II classification errors for all the thresholds evaluated in the grid search. The y-axis reports the True Positive Rate (1 – Type II error) and the x-axis reports the False Positive Rate (Type I error). The origin represents the highest value considered for the threshold (misses all individuals preferring cash payments but avoids misclassifying individuals preferring cash payments). Moving away from the origin along the black 45° line, the value of the threshold declines, reducing type II errors but raising type

I errors. Therefore, the 45° line represents a poor performance (linear combinations of the maximum type II error at the origin with the maximum type I error at the top right corner).

Figure 10: Receiver Operating Characteristic (ROC) curve of the identification of cashless-lover individuals using the digital preference indicator



The ROC curve deviates from the 45° line, indicating that the digital preference measure is effective at identifying individuals who prefer cashless payments. In fact, the AUROC is 0.85. With the loss function parameter set at $\theta = 0.5$, the "optimal" threshold occurs at 0.27 with, individuals with digital preferences equal or over this value classified as preferring cashless payments. Graphically, the value of the threshold is located where the loss function is tangent to the ROC curve (see green line in Figure 10). The higher the θ, the steeper the loss function and the lower the "optimal" threshold.

References

Abramova, S., R. Böhme, H. Elsinger, H. Stix, and M. Summer (2022). What can cbdc designers learn from asking potential users? results from a survey of austrian residents (svetlana abramova, rainer böhme, helmut elsinger, helmut stix, martin summer). *ONB Working Papers* (241).

Andolfatto, D. (2020, 09). Assessing the Impact of Central Bank Digital Currency on Private Banks. *The Economic Journal 131*(634), 525–540.

Assenmacher, K., M. F. Minesso, A. Mehl, and M. S. Pagliari (2024). Managing the transition to central bank digital currency. *ECB Working Papers 2907*.

Auer, R., J. Frost, L. Gambacorta, C. Monnet, T. Rice, and H. S. Shin (2022). Central bank digital currencies: Motives, economic implications, and the research frontier. *Annual Review of Economics 14* (Volume 14, 2022), 697–721.

Bagnall, J., D. Bounie, K. P. Huynh, A. Kosse, T. Schmidt, and S. Schuh (2016). Consumer cash usage: A cross-country comparison with payment diary survey data. *International Journal of Central Banking 12* (4), 1–61.

Berge, T. J. and Ò. Jordà (2011). Evaluating the classification of economic activity into recessions and expansions. *American Economic Journal: Macroeconomics 3* (2), 246–277.

Bijlsma, M., C. van der Cruijsen, N. Jonker, and J. Reijerink (2021, April). What triggers consumer adoption of cbdc? *De Nederlandsche Bank Working Papers* (709).

Bolt, W. and S. Chakravorti (2008). Consumer choice and merchant acceptance of payment media. *Federal Reserve of Chicago Working Papers 11*.

Brown, M., N. Hentschel, H. Mettler, and H. Stix (2020). Financial innovation, payment choice and cash demand–causal evidence from the staggered introduction of contactless debit cards. *ONB Workong Papers 230*.

Candelon, B., E.-I. Dumitrescu, and C. Hurlin (2012). How to evaluate an early-warning system: Toward a unified statistical framework for assessing financial crises forecasting methods. *IMF Economic Review 60* (1), 75–113.

Chiu, J., S. M. Davoodalhosseini, J. Jiang, and Y. Zhu (2023). Bank market power and central bank digital currency: Theory and quantitative assessment. *Journal of Political Economy 131* (5), 1213–1248.

Detken, C., O. Weeken, L. Alessi, D. Bonfim, M. M. Boucinha, C. Castro, S. Frontczak, G. Giordana, J. Giese, N. Jahn, J. Kakes, B. Klaus, J. H. Lang, N. Puzanova, and P. Welz (2014). Operationalising the countercyclical capital buffer: indicator selection, threshold identification and calibration options. *ESRB Occasional Paper Series 5*.

Doerr, S., J. Frost, L. Gambacorta, and H. Qiu (2022). Population ageing and the digital divide. *SUERF Policy Briefs 270*.

Drehmann, M. and M. Juselius (2014). Evaluating early warning indicators of banking crises: Satisfying policy requirements. *International Journal of Forecasting 30*.

ECB (2020, October). Report on a digital euro. techreport, European Central Bank (ECB), 60640 Frankfurt am Main, Germany.

ECB (2022, December). Study on the payment attitudes of consumers in the euro area (space). Technical report, European Central Bank, Frankfurt am Main, Germany.

ECB (2023, October). A stocktake on the digital euro. techreport, Frankfurt am Main, Germany.

ECB (2024). Progress on the preparation phase of the digital euro - second progress report. Technical report, European Central Bank.

Fegatelli, P. (2022). A central bank digital currency in a heterogeneous monetary union: Managing the effects on the bank lending channel. *Journal of Macroeconomics 71*, 103392.

Fegatelli, P. (2024). Monetary policy and reserve requirements with a zero-interest digital euro. *Journal of Macroeconomics 80*, 103597.

Fegatelli, P., G. Giordana, and L. Lebouteiller (2025). From retail payment preferences to macro-financial implications: A bottom-up approach to digital euro design. *BCL working papers* (forthcoming).

Giordana, G. and P. Guarda (2019). Why do social networks introduce virtual currencies? *BCL Working Papers* (132).

Giordana, G. and M. Ziegelmeyer (2024). Using household-level data to guide borrower-based macro-prudential policy. *Empirical Economics 66*(2), 785–827.

Giordana, G. A. and P. Guarda (2025). How digital are we? a model-based measure from survey data. *mimeo*.

Hernandez, L., N. Jonker, and A. Kosse (2017). Cash versus debit card: the role of budget control. *Journal of Consumer Affairs 51*(1), 91–112.

Huynh, K., J. Molnar, O. Shcherbakov, and Q. Yu (2020, March). Demand for payment services and consumer welfare: The introduction of a central bank digital currency. *Bank of Canada Staff working papers* (2020-07).

Kahn, C. M. and J. M. Liñares-Zegarra (2016). Identity theft and consumer payment choice: Does security really matter? *Journal of Financial Services Research 50*, 121–159.

Kaminsky, G., S. Lizondo, and C. M. Reinhart (1998). Leading indicators of currency crises. *Staff Papers-International Monetary Fund*, 1–48.

Keister, T. and D. Sanches (2022, 03). Should Central Banks Issue Digital Currency? *The Review of Economic Studies 90*(1), 404–431.

Kline, R. (2016). *Principles and Practice of Structural Equation Modeling, Fourth Edition* (Fourth ed.). Methodology in the Social Sciences. Guilford Publications.

Kosse, A. (2013, December). The Safety of Cash and Debit Cards: A Study on the Perception and Behavior of Dutch Consumers. *International Journal of Central Banking 9*(4), 77–98.

Kosse, A. (2014). *Consumer payment choices: Room for further digisation?* Ph. D. thesis, Tilburg University.

Kosse, A. and D.-J. Jansen (2013). Choosing how to pay: The influence of foreign backgrounds. *Journal of Banking & Finance 37*(3), 989–998.

Li, J. (2023). Predicting the demand for central bank digital currency: A structural analysis with survey data. *Journal of Monetary Economics 134*, 73–85.

Meyer, J. and F. Teppa (2024). Consumers' payment preferences and banking digitalisation in the euro area. *ECB Working Papers* (2915).

Nocciola, L. and A. Zamora-Pérez (2024). Transactional demand for central bank digital currency. *ECB Working Papers* (2926).

Pulina, G. (2023). Consumer debt in luxembourg and the euro area: Evidence from the household finance and consumption survey. *BCL Working Papers* (175).

Schuh, S. and J. Stavins (2010). Why are (some) consumers (finally) writing fewer checks? the role of payment characteristics. *Journal of Banking & Finance 34*(8), 1745 – 1758. New Contributions to Retail Payments: Conference at Norges Bank (Central Bank of Norway) 14-15 November 2008.

Stokey, N. L. (2021). Technology diffusion. *Review of Economic Dynamics 42*, 15–36.

Van der Cruijsen, C., L. Hernandez, and N. Jonker (2017). In love with the debit card but still married to cash. *Applied Economics 49*(30), 2989–3004.

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