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Research Paper

Internalizing match-dependent externalities [☆]

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ABSTRACT

External effects can be triggered through trade and depend on the locations of buyers and sellers who are matched. Inspired by electricity markets, we experimentally investigate markets in which net trades between two locations induce social costs. Based on a modified double auction setting, we compare the performance of market platforms that are location-blind with those where information on the location of (potential) trading partners or the level of the externality is given. We demonstrate that locational information is sufficient to reduce the externality. Imposing the full external costs on individual trades leads to maximal price differentiation between locations and further reduces net trades, while welfare improvements are limited. Reasons for not achieving the typically high efficiency of double auctions are discussed.

1. Introduction

Internalizing external effects is at the heart of many regulatory interventions. Externalities may arise from production or consumption, yet often they are created through trade and thereby depend on the match between buyers and sellers.

A typical example is external effects arising from transporting products. Calls for “buying local” reflect awareness for these issues.[1] Yet, in many market platforms, market participants lack information on the location of potential trading partners. As shipping rates within a country are often independent of the distance, it makes no difference for a consumer whether he buys from a store that is around the block or on the other side of the country, even though the actual costs of shipping and potential externalities differ (e.g., Anderson et al., 2003).

Electricity markets are another example where the match between buyers and sellers can generate external effects due to capacity constraints of transmission lines. In Europe, electricity markets largely rely on zonal pricing with a zone often equaling a country. The price *within* a zone is uniform, i.e. it is assumed that there are no transmission restrictions within the zone (e.g., Bjorndal and Jornsten, 2001; Weibelzahl, 2017). Yet, this assumption is particularly challenged in times of a larger market integration of renewables. As a consequence, network operators carry out expensive re-dispatching activities at an increasing scale. The arising

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[1] Buying locally is frequently advertised based on environmental benefits, among others (e.g., http://www.gogreen.org/blog/the-environmental-benefits-of-buying-locally, https://sustainableconnections.org/why-buy-local/, even though critical assessments exist, (e.g., Ferguson and Thompson, 2021)).

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costs are reallocated to all market participants as they belong to the costs of maintaining the grid.[2] While trades between market participants at different sides of a congested line thus impose externalities on other market participants,[3] the market setting typically provides neither locational information nor incentives to take the external effect into account.

In both these examples, externalities thus depend on which market participants trade while the underlying market designs limit their internalization. Yet, they differ in one important detail: while transportation externalities depend on the spatial distance between sellers and buyers, i.e. the total number and length of trips, the externalities arising from congestion in electricity grids depend on the *net* trades, i.e. trades can also alleviate the congestion and thus externality if the trade occurs in the opposite direction of the congestion.

In this paper, we provide evidence from a laboratory auction experiment to demonstrate how such match-dependent externalities can be countered. Our design has buyers and sellers located in two locations. The externality depends on the *net* trades between the locations. While we thus concentrate on the example of congestion within (zonal) electricity markets, the lessons on (partially or fully) addressing the externalities in spatial contexts apply more widely.

Our treatments vary the depth of market intervention. We first investigate how (i) information on the location of market participants or (ii) information on the current congestion level, i.e. the marginal externality triggered through a potential trade, affect market efficiency. In these treatments, the burden arising from the externality is distributed equally onto all market participants, corresponding to the distribution of redispatch costs in electricity markets via grid costs. We compare these information treatments to full internalization where market participants have to bear the external costs triggered through their trade.[4] Only such full internalization is predicted to lead to the optimal price differentiation between regions, similar to the one achieved by nodal pricing in our guiding example of electricity markets.

We find that providing information on locations of buyers and sellers already leads to spatial price separation and reduces the externality resulting from net trades. Full price separation and a further reduction of net trades and, hence, the externality occurs when individual market participants are forced to fully internalize the externality arising from their individual trades. Yet, providing locational information or incentives for internalizing the external benefits into the market also comes at a cost. As the benefits from trade depend on who one is selling to or buying from, i.e. on the locational match, the ability of markets to achieve the maximal surplus is impaired. Trading off these efficiency costs with the reduction of the externalities, the welfare gains from their internalization only materialize if externalities are sufficiently steep.

The remainder of the paper proceeds as follows: we discuss related literature in Section 2. Section 3 provides the theoretical foundation, Section 4 reports the experimental design, predictions, and experimental procedures, before we discuss the results in Section 5. The final Section concludes.

2. Related literature

With our experimental design, we modify the typical double auction environment to allow for location specific offers. In practice, a majority of electricity markets are designed as auctions and modelled accordingly in the literature (e.g., Gianfreda et al., 2018; Bosco et al., 2010). Within the European electricity market, electricity is traded through over-the-counter (OTC) trading, the spot market, and the intraday market. While OTC markets are primarily defined by search frictions (see Chamberlin, 1948), the spot and intraday markets are implemented as more centralized auctions. The spot market is set up as a clearinghouse auction (Cason and Friedman, 1997) and deals with trades where delivery lies at least 24 hours in the future. The intraday market uses double auctions and accommodates short-term (≤24 hours) trading in order to manage fluctuations in electricity demand and production. This makes this market particularly relevant for intermittent producers, such as wind and solar power which are substantial contributors to grid congestion (Goop et al., 2017). They are met with consumers with a high degree of flexibility in their consumption. These are the specific kinds of traders that can generate and alleviate match-dependent externalities. The share of intraday trading has been increasing since 2015 and currently covers roughly one fifth of trades on the main trading platform in Europe.[5] This makes the intraday market and the corresponding double auction most relevant for our analysis and setting.

Double auctions are typically a highly efficient market mechanism to match buyers and sellers (Ketcham et al., 1984; Friedman, 1984; Smith, 1962).[6] They typically converge towards equilibrium rather fast (Smith, 1962) which is especially suitable to our experiment as the introduction of an externality and locational information makes traders' choices more complex. Our theoretical guidance relies on equilibrium predictions which – in principle – also apply to clearinghouse auctions and OTC markets with the caveat of lower reduced efficiency and convergence in these alternative market designs (e.g., Attanasi et al., 2016; Friedman, 1993).

Only few papers incorporate externalities in experimental market settings. The main focus is on flat per-trade externalities, as in Plott (1983), who finds no evidence for individuals reacting to the externality in the absence of internalization. A recent literature

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[2] The costs can be substantial (e.g., Egerer et al., 2016; Hirth et al., 2019). For example, the largest German grid operator spent more than one billion euros on redispatch or on compensating curtailment of renewables due to grid constraints https://www.reuters.com/article/us-tennet-germany-idUSKCN1PS0FI. Further efficiency gains can be obtained from better market couplings across zones (e.g., Parisio and Pelagatti, 2019).

[3] The externalities also include environmental effects if renewables are replaced by fossil-based production.

[4] This is in line with nodal pricing, a mechanism that is applied in some electricity markets, mainly USA and South America (see Hogan, 1998; Schweppe et al., 2013). The mechanism allows for differentiated prices that take the capacity constraints into account, but may come at costs of highly differentiated prices or market power (e.g., Weibelzahl, 2017).

[5] On EPEX Spot, intraday trading made up 123 TWh in 2021, compared to 498 TWh traded on the spot market (EPEX, 2022).

[6] Double auctions are also used to experimentally study markets in other applications, e.g. asset markets (Smith et al., 1988; Lugovskyy et al., 2014; Guler et al., 2021; Baghestanian et al., 2015).

finds that individuals are willing to voluntarily internalize market externalities that affect uninvolved individuals (e.g., Bartling et al., 2015, 2019; Sutter et al., 2020). There is, however, evidence towards a lower concern for the externality in a market setting compared to a neutral one (Falk and Szech, 2013).

Our setting differs from these studies: (i) The externality caused by a trade depends on which individuals matched in a trade and where they are located: a trade can either cause no externality (trade within location), a positive or a negative externality, depending on whether it increases or decreases the congestion. For example, the external effect arising from taking up a given seller's offer, depends on the buyer's location relative to the seller's location, and additionally on the current market condition (congestion level). The externality can thus not only be countered by reducing the number of trades, but also by better matches between the locations of trading partners. The role of information on market participants' locations as well as fitting market conditions have not been addressed in the extant literature. (ii) The externality is rolled over to market participants themselves, rather than a third party. While this setting is highly relevant in electricity markets and relates to the experimental design in Plott (1983), it also corresponds to typical common pool or public good settings where the externality is born by the causing group itself. (iii) We do not only study voluntary internalization efforts, but also consider conditions under which market designs enable (partial) internalization of the externality and the realization of welfare gains.

By providing information on the location of buyers and sellers, the units offered or requested in the auctions become spatially differentiated. With this, our study is related to the literature on auctions that allow for individual valuations of auction items to depend on multiple attributes (e.g., Bichler, 2000; Che, 1993). The main difference in our setting is that the additional quality, i.e. location, only impacts the externality and not directly the market participants' own valuations or costs.

3. Theoretical guidance

We model a market for a homogeneous good with buyers and sellers with private valuations. Buyers and sellers are located at two locations A and B. Guided by our example of zonal pricing in electricity markets as discussed in the introduction, these locations are both within a zone, but on opposite ends of a (potentially) congested transmission line. In location $l \in \{A, B\}$, the aggregate (inverse) demand of n_l buyers is given by $P_l(X_l)$ (decreasing), while the costs of sellers $j = 1, \dots, m_l$ are given by $C_l^j(y_l^j)$ (increasing convex). We denote aggregate supply in location l by $Y_l = \sum_j y_l^j$. Any feasible allocation needs to balance demand and supply, i.e. $X_A + X_B = Y_A + Y_B$. Guided by the example of electricity markets and the externalities arising from capacity constraints between locations, we assume that externalities d depend on the net trade between locations, that is on the extent of transportation from A to B and vice versa. This is given by the excess demand in B, $X_B - Y_B$, or equivalently by the excess supply in A, $Y_A - X_A$. Thus, $d = D(X_B - Y_B)$. Note that net trade can go in either direction, i.e. $X_B - Y_B$ can be positive or negative. For simplicity, we assume that $D(\cdot)$ is symmetric, i.e. $D(z) = D(-z)$, with $D(z)$ decreasing in z for $z < 0$, increasing for $z > 0$ and convex.

The welfare in any feasible allocation (satisfying $X_A + X_B = Y_A + Y_B$) is thus given by:

$$\int^{X_A} P_A(s)ds + \int^{X_B} P_B(s)ds - \sum_j C_A^j(y_A^j) - \sum_j C_B^j(y_B^j) - D(X_B - Y_B). \tag{1}$$

Welfare maximization, i.e. maximization of (1) requires

$$p_A = P_A(X_A) = C_A^{j\,\prime}(y_A^j) \tag{2}$$

$$p_B = P_B(X_B) = C_B^{j\,\prime}(y_B^j) \tag{3}$$

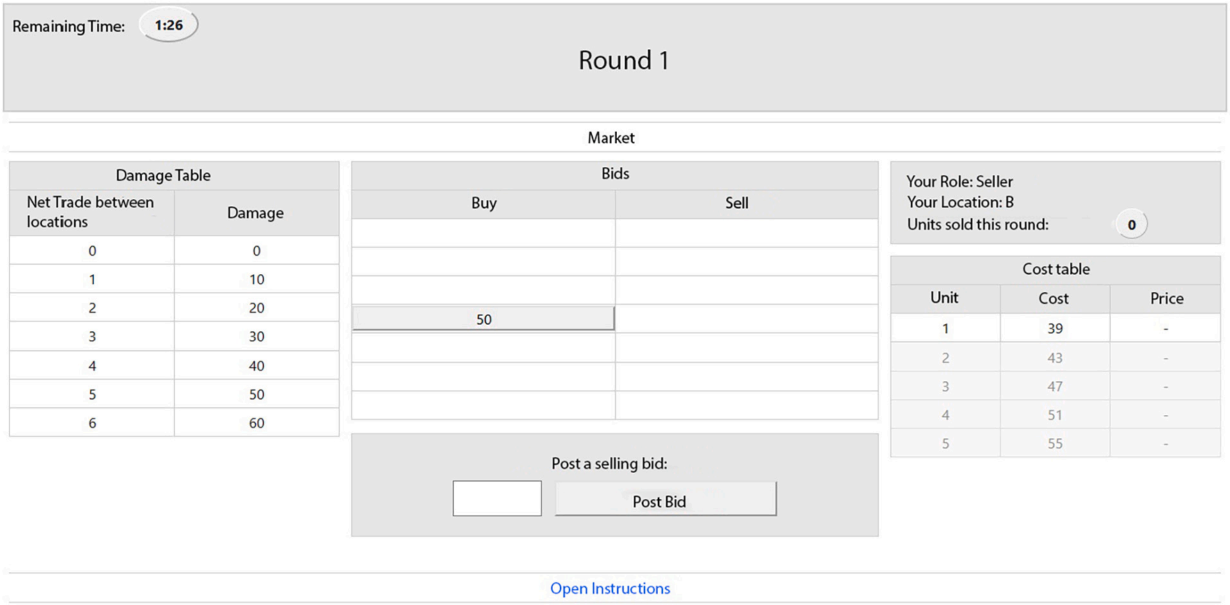
$$p_B - p_A = D'(X_B - Y_B). \tag{4}$$

Here, (2) and (3) state the typical conditions that the price needs to equal marginal costs within a location. The intuition is that no externality arises from a trade between buyers and sellers located at the same location. Yet, (4) shows the potential of a price differential between the two locations. If net trade flows from A to B, i.e. if $X_B > Y_B$ (positive excess demand in location B), an additional trade from A to B increases the externality ($D'(X_B - Y_B) > 0$) such that the price (and marginal costs) within location B are larger than in A. The opposite effect happens if location A has positive excess demand and trade flows are reversed ($p_B - p_A = D'(X_B - Y_B) < 0$). The price differential thus optimally reflects the marginal externality arising the marginal trade between the two locations.

Assuming competitive market behavior, this welfare optimum can be decentralized by charging a tax τ for trade from A to B at a rate of $D'(X_B - Y_B)$. Then, a firm located in A is indifferent at the margin between selling within A (obtaining a price p_A) or selling to a buyer in B and thus obtaining a revenue of $p_B - \tau (= p_A)$ for the last trade. A similar argument holds for firms in B for whom a trade with buyers in A would essentially be subsidized: $p_B = p_A + \tau$. That is, selling within B gives a price of p_B, while selling into A would give them not only the price p_A, but also an additional subsidy τ.

Yet, such decentralization does not only necessitate imposing such a tax to internalize the externality, but also requires market participants to know the location of their trading partners. If this information is not present, prices cannot be differentiated between locations. In this case, the prices in both locations will be equal:

$$p = P_A(X_A) = P_B(X_B) = C_A^{j\,\prime}(y_A^j) = C_B^{j\,\prime}(y_B^j) \tag{5}$$



Remaining Time: 1:26

Round 1

Market

Damage Table	
Net Trade between locations	Damage
0	0
1	10
2	20
3	30
4	40
5	50
6	60

Bids	
Buy	Sell
50	

Your Role: Seller
Your Location: B
Units sold this round: 0

Cost table		
Unit	Cost	Price
1	39	-
2	43	-
3	47	-
4	51	-
5	55	-

Post a selling bid:

Fig. 1. Screenshot of market platform, *baseline* treatment.

As maximizing welfare requires prices to differ between locations as stated by (4), the damages D under uniform prices are larger than optimal. Clearly, the same equilibrium allocation results even if the locations of trading partners are known, but no internalization of externalities is induced by taxes like described above.

Within electricity markets, the costs arising from congestion are typically rolled over to market participants as part of the costs for maintaining the grid and, thus, independently of who actually caused the externality. While this implies that part of the externalities are borne by those who conclude a specific trade, no effect on behavior can be expected if markets are competitive. Yet, in case of a small number of market participants – as given in our experimental setting – the roll over of the external costs will lead to partial internalization, i.e. prices being differentiated by a fraction of the marginal externality.

4. Experimental design and procedures

4.1. Experimental design

We embed the idea of match-dependent externalities in a multi-unit double auction experiment. We first review the market platform before discussing the treatments.

The market platform. Our market platform matches sellers with buyers and assigns prices to each trade. Participants interact in groups of eight traders, comprised of four sellers and four buyers. The role and group of the participants stay fixed throughout the experiment. Two sellers and two buyers are assigned to each location, A or B, respectively.[7] A trader always knows his own location, which is fixed across periods. The information given about the origin of bids on the auction platform depends on the treatment.

Sellers are endowed with five units of the tradable good, and buyers can buy a maximum of five units and are not allowed to resell any units they bought. This limits the maximum number of trades to five for each trader. Each buyer (seller) is randomly assigned a vector of valuations (costs) for the respective five units per participant. For buyers, the profit from acquiring a unit is calculated by subtracting the price paid from the valuation. Vice versa, for sellers the profit is the difference between the price received and the cost.

Buyers and sellers can submit bids/asks on the market platform, and can accept offers from the opposite role. The market is specified further by the following rules: offers and offer acceptance are only allowed if the trader at least breaks even with the resulting trade.[8] This break-even requirement for trades does not take the externality into account. Further, bids and asks that match with respect to price do not automatically result in a trade. Instead, offers have to be specifically accepted by another buyer/seller. This is done by clicking on the corresponding offer, see Fig. 1 for an example of the market platform. We note that this feature slightly differs from the traditional double auction setting (e.g., Ketcham et al., 1984; Friedman, 1984; Smith, 1962), but is also implemented in other studies, such as Attanasi et al. (2016, 2021). As a consequence of this feature, posting an offer gives no control over the

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[7] We chose to have two sellers and two buyers in each location in order to prevent locational market power. Typically, under double auction trading, having at least two traders per role suffices to result in competitive outcomes, even with unequal numbers of buyers and sellers (e.g. Plott, 1982; Smith, 1982; Attanasi et al., 2021).

[8] This feature is important for promoting learning and convergence, see Gode and Sunder (1993, 1997).

Table 1
Overview over all 8 treatments.

		Externality	
		Linear	Exponential
Market Manipulation	Baseline	$baseline_L$	$baseline_E$
	Locational	$locational_L$	$locational_E$
	Indicator	$indicator_L$	$indicator_E$
	Internalization	$internalization_L$	$internalization_E$

location of the trading partner who eventually accepts the offer. The accepting trader, however, can decide where to sell/buy from if the necessary information is given. Thus it is necessary that lower bids or higher asks are not immediately replaced and both bids and asks of the same value are allowed, as they may originate from different locations. Once an offer is accepted, the trade is administered and the market is cleared of all offers and players can post a new set of offers as long as the trading round has not ended.[9]

Each round lasts a total of two minutes. After that, the traders get an overview of their financial gains. This includes paid/received prices, valuations of the units bought or costs of units sold, and the costs arising from the externality. Each group of traders plays for a total of 16 rounds, to give enough time for prices to converge.

As described above, the structure of the externality is inspired by electricity markets and depends on the number of net trades from one location to the other. That is, trades in different directions offset each others' externality. Further, we assume symmetry such that the direction of net trades does not matter.

The treatments. Our treatments vary along two dimensions: first, the market design and, second, the form of the externality. Table 1 gives an overview over the treatments. The market design dimension varies the information that traders get from the trading platform and how the burden of the externality is distributed across market participants. In all treatments except *internalization* the externality is socialized, so each trader pays one eighth of the total externality costs. These treatments vary in the information provided to traders. Under the *baseline* treatment traders only know their own location. There is no additional information on the origin of any offer. Treatment *locational* introduces this information by displaying the location an offer is from next to it on the platform. This information is public information within each group. This enables traders to take into account the effect that accepting an offer may have on the externality. Specifically, by accepting a offer from the trader's own location, no externality can arise. Accepting an offer from the other location can both reduce or increase the externality. Treatment *indicator* additionally shows a box with information on the current net trades including the direction, the corresponding externality cost, and the share of the cost the trader has to pay. As before the information is available to all traders within each group. Thus, traders can anticipate the effect of each trade on the total externality as well as on their share of external costs. Finally, in treatment *internalization*, the marginal externality induced by a specific trade is directly imposed on the accepting trader only. Prices are then directly changed for each individual trader on the platform, according to the externality damages that are created or eliminated by the potential trade. Traders can also directly observe how an offer is changed, as can be seen in Fig. 2. The treatment also includes all market information given in the *indicator* treatment.

The second treatment dimension varies the shape of the externality function, i.e. compares a linear and exponential externality costs. Both types of externality speak to different real-life scenarios, with linearity fitting better to transmission losses while exponentiality fits more to congestion costs through load management such as redispatch. A further reason to include both forms of the externality is that it impacts the relevance of information given about the current net-trades: for a linear externality, the marginal externality is constant such that information on the direction of the congestion is sufficient. For the exponential (or in fact any convex) externality, the marginal externality costs are increasing with the *extent* to which the line is congested, i.e. the number of net trades that have already occurred.

The parameter choices. Table 2 shows the valuations and costs induced on participants in the respective locations. These are noted in experimental currency units (ECU). To make sure there is a market incentive to trade across locations, both costs and valuations are designed to be 8 ECU lower in location A. This makes A an export location and B an import location. The exact values of the externality are shown in Table 3. The externality can be represented by $D(|X_B - Y_B|) = 10|X_B - Y_B|$ for the linear form and $D(|X_B - Y_B|) = 5\sum_{i=0}^{|X_B-Y_B|} i = 5(|X_B - Y_B|)(|X_B - Y_B| + 1)/2$[10] for the exponential form. In all but the *internalization* treatment the costs of the externality are shared between all market participants in equal parts, independent of the number of units traded. In order to prevent participants ending up with negative profits, traders receive 10 ECU at the end of each round.

While the market design dimension is investigated in a between-subjects design, the externality dimension is varied in a within-subject design. Specifically, the individual valuations and costs and the externality type both change after round 8. The starting externality type is randomized within each treatment to account for order effects. The traders are previously informed that a change will happen, but not in which way. Note again that neither a trader's role nor his location change at any time.

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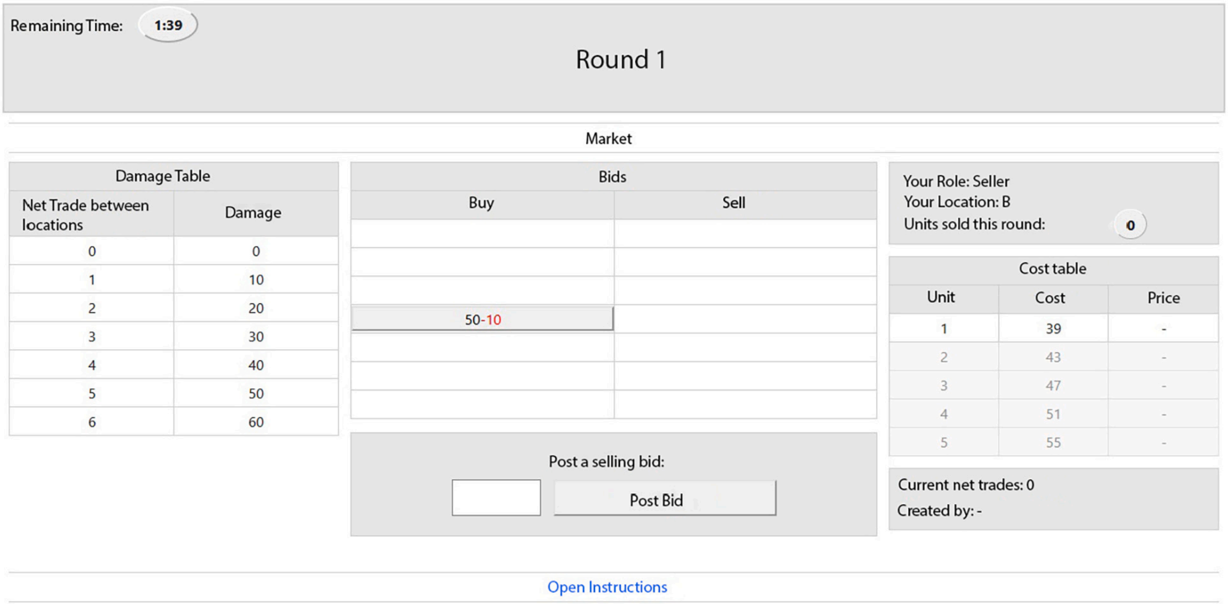
[9] This feature is also present in Attanasi et al. (2016, 2021).

[10] This formula represents an externality with a marginal externality that increases by 5 ECU for each net trade. We chose this relatively simple form to make it easy to understand for participants.



Remaining Time: 1:39

Round 1

Market

Damage Table

Net Trade between locations	Damage
0	0
1	10
2	20
3	30
4	40
5	50
6	60

Bids

Buy	Sell
50-10	

Post a selling bid:

Your Role: Seller
Your Location: B
Units sold this round: 0

Cost table

Unit	Cost	Price
1	39	-
2	43	-
3	47	-
4	51	-
5	55	-

Current net trades: 0
Created by: -

Fig. 2. Screenshot of market platform, *internalization* treatment.

Table 2
Valuations of buyers (B1 and B2) and costs of sellers (S1 and S2) in locations A and B.

	Location							
	A				B			
Unit	S1	S2	B1	B2	S1	S2	B1	B2
1	31	33	55	53	39	41	63	61
2	35	37	51	49	43	45	59	57
3	39	41	47	45	47	49	55	53
4	43	45	43	41	51	53	51	49
5	47	49	39	37	55	57	47	45

Table 3
Externality costs as a function of net trades between location A and B.

Net trades $\|X_B - Y_B\|$	External costs $D(\|X_B - Y_B\|)$	
	Linear	Exponential
0	0	0
1	10	5
2	20	15
3	30	30
4	40	50
5	50	75
6	60	105

4.2. Predictions

We rely on competitive equilibria in the respective treatments for deriving predictions. We first start with discussing the prices, net trades, trade surplus and welfare in these equilibria. Table 4 summarizes these levels. Note that we define efficiency as the realized welfare divided by the maximum achievable welfare.[11]

The right panel in Fig. 3 illustrates excess demand for location B and excess supply for location A, along with the predictions for prices and net trades for each treatment. In the *baseline* treatment, no information on locations of trading partners is given. We thus

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[11] Note that the maximum welfare results under internalization and depends on the form of the externality (168 or 171, respectively, under the linear or exponential externality). The valuations are given in Table 2 and externalities are chosen such that the predicted prices and number of trades in baseline, locational, and indicator treatments do not depend on the type of externality.

Table 4
Overview over theoretical predictions for each treatment.

Treatment	p_A	p_B	Net-trades	Externality D	Trade Surplus	Welfare	Efficiency
$baseline_L$	47	47	4	40	184	144	0.86
$locational_L$	46	48	3	30	184	154	0.92
$indicator_L$	46	48	3	30	184	154	0.92
$internalization_L$	43	51	0	0	168	168	1.00
$baseline_E$	47	47	4	50	184	134	0.78
$locational_E$	46	48	3	30	184	154	0.90
$indicator_E$	46	48	3	30	184	154	0.90
$internalization_E$	43	51	1	5	176	171	1.00

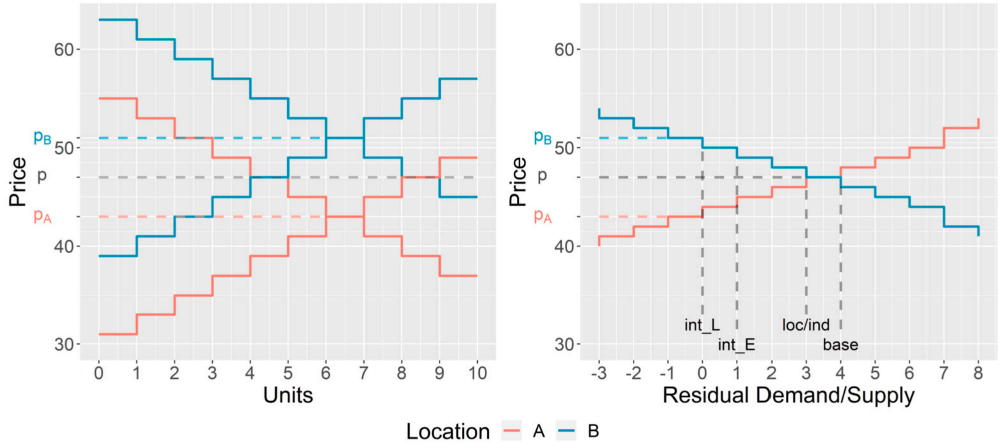

Fig. 3. Market supply and demand (left panel) and excess demand for location B and excess supply for location A (right panel). p_A and p_B indicate autarky prices. base, loc/ind, int_L and int_E mark treatment predictions of the corresponding treatment.

expect an equilibrium price of $p = 47$ with 4 net trades from A to B. In particular, prices should not differ between the two locations. As this treatment is most similar to the traditional double auction, we also expect similar convergence towards the equilibrium.[12]

Treatment *internalization* imposes the full external cost onto the accepting trader. We thus expect a separation of prices in the two locations. Maximal price separation occurs under autarky, i.e. without any external trade with price levels given by $p_A = 43$ and $p_B = 51$ as illustrated in Fig. 3. For the linear externality variant, the marginal external costs triggered by any additional net trade are given by 10 units. Thus, we expect zero net trades as the price difference in autarky is smaller than the marginal external costs. For the exponential externality, the marginal external costs for the first trade are 5 such that we expect one net trade from A to B to occur in equilibrium under internalization. The left panel of Fig. 3 illustrates market supply and demand and the corresponding equilibrium prices, both for autarky and in a shared market. The right panel indicates the residual supply (demand) for location A (B), calculated as the difference between supply (demand) and demand (supply) for any given market price. The panel also illustrates that the excess demand of one unit is decentralized with $p_A = 44$ and $p_B = 50$.[13]

The specific units that are traded in the equilibria in the *baseline* and the *internalization* treatments are illustrated by the shaded entries in Tables A.13–A.16.

In the *baseline*, *locational* and *indicator* treatments each player takes on one eighth of the total externality costs. Different from the *baseline* treatment, players know the location of their trading partners in the *locational* and *indicator* treatments and thus may take this partial internalization into account. If they do, the equilibrium predictions involve prices differentiated by location, $p_A = 46$ and $p_B = 48$ and a net trade of three units.[14] While the prediction is numerically the same, the locational treatment gives less information to traders in that the current level of externality is not known. Comparison between the two treatments allows insight into how much information needs to be provided to a market in order to reach efficient outcomes. While the provision of locational information is relatively easy to implement in electricity markets, calculation and access to on-time grid usage costs requires significantly more investment.

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[12] For recent examples on double auction convergence, see, e.g., Attanasi et al. (2016, 2021).

[13] Note that due to the discrete trading options, the price difference is not exactly at the level of the marginal externality. The prices are limited to natural numbers.

[14] Note that the marginal external costs from an additional net trade are $10/8 = 1.125$ under linear externalities, while a fourth net trade would impose and externality of $20/8 = 2.5$ for the exponential externality, while relaxing the externality by trading the opposite direction reduces the externality by $15/8 = 1.875$. Given the prices p_A and p_B, there is no incentive for any market participant to trade an additional unit: sellers in A (B) would get p_A $(p_A + (D(3) - D(2))/8)$ for selling an additional unit into A, $p_B - (D(4) - D(3))/8$ (p_B) for selling into B. Buyers in A (B) pay p_A $(p_A + (D(4) - D(3))/8)$ when buying an additional unit in A, and $p_B - (D(3) - D(2))/8$ (p_B) when buying in B.

Given the sequential nature of the experimental double auction, not all units are necessarily traded at an identical price. In particular, in treatment *internalization*, the traders are charged different amounts for the externality, depending on when they trade. For example, the first trade between A and B necessarily imposes an externality of $D(1)$ which is charged to the accepting trader. In case that a second trade occurs in the same direction, the accepting trader will be charged $D(2) - D(1)$. Should a third trade occur in the opposite direction, the corresponding accepting trader would receive a subsidy of $D(2) - D(1)$. We thus may see different price offers over time depending on the current level of net trades. At the same time, this dynamic may lower convergence rates towards the equilibrium. While this holds primarily for the *indicator* and *internalization* treatments, it can also have an effect on the other treatments, if traders form expectations over the current marginal externality.

The qualitative predictions on treatment differences can be summarized as follows:

(i) Prices differentiate between locations in the *indicator* and *locational* treatments compared to the *baseline*. The extent of differentiation is larger in the *internalization* treatment compared to the other treatments.
(ii) The number of net trades is largest in the *baseline*, reduced in *locational* and *indicator*, and even smaller in the *internalization* treatments.
(iii) The welfare is largest in the *internalization* treatment. In *locational* and *indicator* treatments, welfare is larger than in the *baseline* treatment.

4.3. Experimental procedures

The experiment was conducted online at the WiSo Forschungslabor at University of Hamburg, using the standard in-person participant pool. The experiment was conducted online due to COVID-19 restrictions, see Buso et al. (2021, 2020) for a discussion about the differences between online and lab experiments during the pandemic. Participants were invited via hroot (Bock et al., 2014). The experimental software used was oTree (Chen et al., 2016). A total of 288 participants ran through the experiment. Four groups had at least one participant drop out,[15] and have been repeated with new participants, resulting in 256 participants balanced over all 4 market design treatments variants. We thus have data on a total of 32 groups of 8. The data is also balanced within each market design treatment with respect to the order in which the externality cost structures are applied.[16]

Participants received 5 € as show-up fee. In addition, one round was randomly selected at the end of the experiment for payout. For each ECU 0.50 € were paid out, resulting in an average payout of 19.75 € per participant. With fixed timeouts for introduction and rounds, the maximum time spent on the experiment was about 60 minutes, resulting in above average wages for participants at the lab at University of Hamburg.

5. Results

The data-set consists of 37131 individual offers, with a total of 6320 units traded, resulting in 17.02% of offers being accepted. On average, each trader bought or sold 3.09 units each round.

In Section 5.1, we first consider the treatment effects averaged across rounds. We consider the effects on prices, net trades (and the resulting externalities), and welfare in Section 5.2. We additionally discuss in detail which units end up being traded to better understand the impact of treatments on surplus and welfare. Section 5.3 then considers the temporal structure, i.e. convergence properties.

5.1. Average treatment effects

Table 5 shows the prices that result in location A and B as well as the test statistics for price differentiation. The locational last prices are defined as the price of the last unit sold from the corresponding location. This can be either a within-location location trade or a trade between locations. The final average offers are also illustrated in Fig. 4. Observations are pooled at the group level over all rounds with the same externality cost structure (*linear* (L) or *exponential* (E)). This applies for all statistical tests reported in this section. Corresponding linear regressions are shown in Tables A.17–A.20.

In the *baseline* treatments, there are only minor differences between prices in the two locations ($|p_A - p_B|$ averaging to $0.91(L)$ and $0.42(E)$, respectively, $pval(L) = 0.06$, $pval(E) = 0.21$, Wilcoxon signed rank). As predicted, the *internalization* treatments lead to significant price differentiation under both linear and exponential externality ($pval < 0.01$ $(L\&E)$, Wilcoxon signed rank). In fact, the difference is significantly larger than in the *baseline* treatment for both variants of externality ($pval < 0.01$ $(L\&E)$, Mann-Whitney rank sum test). Table 5 reveals that the treatments *locational* and *indicator* already lead to significant price differentiation under linear externality. However, the extent of differentiation does not significantly differ from the *baseline* treatment ($pval > 0.10$ for both treatments $(L\&E)$, Wilcoxon rank sum).[17] Under exponential externality, there is price differentiation in the *indicator*

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[15] Participants are considered dropouts when the browser accessing the experiment was closed and not reopened again. The 32 participants in the 4 groups with dropouts have not been included in the data analysis.

[16] No order effects can be identified.

[17] Conversely, the differentiation in the *internalization* treatment is larger than in any other treatment ($pvals < 0.01$, Wilcoxon rank sum, for both externality variants).

Table 5

Last price (p), average price (p_{av}), locational last prices (p_A, p_B, based on seller location), price differences ($|p_A$-$p_B|$), p-values from Wilcoxon signed rank tests on equality of locational prices (pval $p_A = p_B$), by externality type and treatment.

Treatment	p	p_{av}	p_A	p_B	$\|p_A$-$p_B\|$	pval $p_A = p_B$
$baseline_L$	47.06	44.09	46.33	47.24	0.91	0.06
$locational_L$	46.70	46.45	46.36	48.08	1.72	0.02
$indicator_L$	46.48	45.89	45.41	47.34	1.94	0.02
$internalization_L$	47.42	47.52	44.81	50.83	6.02	0.01
$baseline_E$	46.58	44.89	46.50	46.92	0.42	0.21
$locational_E$	47.39	47.08	46.94	48.41	1.47	0.16
$indicator_E$	47.02	45.60	46.38	48.00	1.62	0.04
$internalization_E$	44.78	46.53	43.69	48.03	4.34	0.01

Table 6

Number of actual trades.

Treatment	Actual Trades				
	Total	A to A	B to B	A to B	B to A
$baseline_L$	12.61	3.41	2.89	4.66	1.66
$locational_L$	12.77	3.83	4.17	3.73	1.03
$indicator_L$	12.14	4.25	3.44	3.39	1.06
$internalization_L$	12.08	5.05	4.97	1.16	0.91
$baseline_E$	12.47	3.19	3.02	4.91	1.36
$locational_E$	12.34	3.83	4.05	3.36	1.11
$indicator_E$	12.11	3.70	3.39	3.73	1.28
$internalization_E$	12.23	4.91	4.84	1.56	0.92

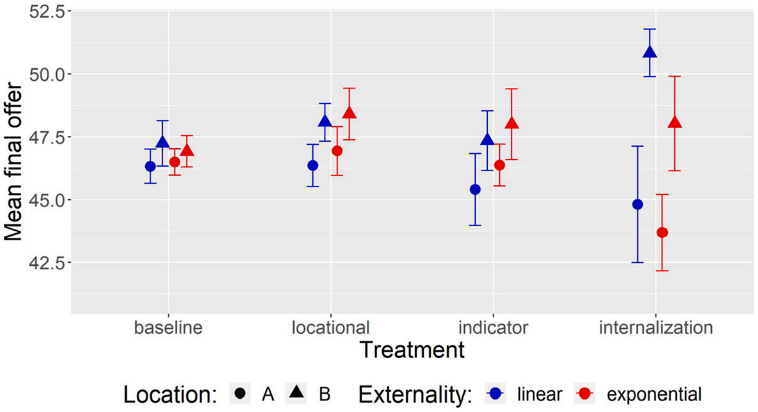

Fig. 4. Average final offer for each treatment. Observations are pooled over all rounds on the group level. Error bars show 95% confidence intervals.

treatment, but not in the *locational* treatment. Yet, the price differentiation is not significantly different between the two treatments ($pval > 0.10$, Wilcoxon rank sum).

While the price differentiation indicates that the treatments indeed affect the prices and thus the trade decisions within and between locations, the welfare properties are clearly determined by the units that are actually traded. Table 6 delineates the trades by locations. We first note that the total number of traded units varies in the treatments between 12.08 ($internalization_L$) and 12.77 ($locational_L$) and thus falls short of the predicted number of 14 traded units. We also note that trades occur in both directions, that is from A to B and from B to A, with more trades going from A to B as predicted. Within the *internalization* treatments, this also implies that some trades are taxed while others are subsidized. Further, the *internalization* treatments show a decrease in the amount of units traded from A to B, compared to the other treatments (individual $pvals < 0.00$ ($L\&E$), Wilcoxon rank sum, see Tables A.3, A.4). This is in line with the price mechanism preventing cross-trades. The effect is not present for trades from B to A (see Tables A.5, A.6), due to trades in this direction being rare to begin with.

The average net trades range from 3.00 (L) and 3.55 (E) in the *baseline* treatments, to 0.31(L) and 0.64(E) in the *internalization* treatments as reported in Table 7 and illustrated in Fig. 5. Net trades in the $locational_L$ and $indicator_L$ treatments are not significantly smaller than in the $baseline_L$ treatment. Only $internalization_L$ reduces net trades relative to all other treatments with linear externality ($pval < 0.01$, Mann-Whitney U test, see Table A.1). Different treatment effects result for the exponential externality: here, $locational_E$ and $indicator_E$ treatments are sufficient to reduce the net trade relative to the $baseline_E$ ($pval = 0.004$ and $pval = 0.074$,

Table 7
Net trades, externality damage, trade surplus, welfare and efficiency by externality type and treatment; efficiency is calculated based on the percentage of maximum welfare, including externality (168 for linear, 171 for exponential externality) that is achieved.

Treatment	|Net-trades|	Externality D	Trade Surplus	Welfare	Efficiency
$baseline_L$	3.00	30.00	174.78	144.78	0.86
$locational_L$	2.73	27.34	173.09	145.75	0.87
$indicator_L$	2.39	23.91	166.75	142.84	0.85
$internalization_L$	0.31	3.13	149.94	146.81	0.87
$baseline_E$	3.55	43.67	174.50	130.83	0.77
$locational_E$	2.34	24.06	169.03	144.97	0.85
$indicator_E$	2.52	27.03	164.06	137.03	0.80
$internalization_E$	0.64	3.60	154.53	150.94	0.88

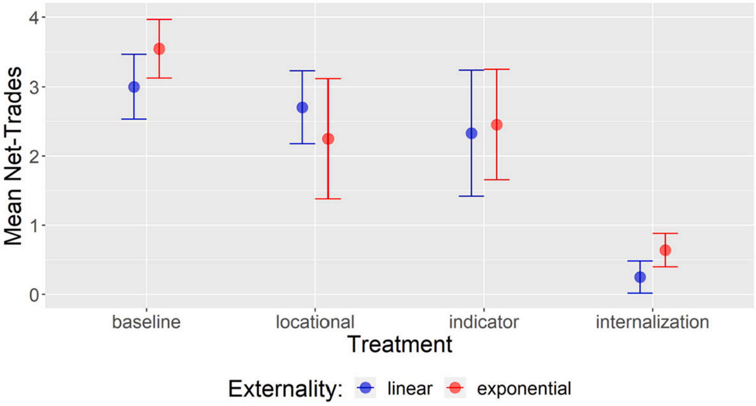

Fig. 5. Average end-of-round net trades for each treatment. Observations are pooled over all rounds on the group level. Errorbars show 95% confidence intervals.

respectively, Mann-Whitney U test). Treatment $internalization_E$ further reduces the average net trade relative to all other treatments ($pval < 0.01$, Mann-Whitney U test, see Table A.2).

We thus obtain that providing locational information or indicating the current level of externalities can already reduce the externality resulting from net trades. We note that the reduction is significant when it is particularly important under the exponential externality variant as here the marginal benefits from reducing the congestion are largest.

5.2. Welfare and efficiency

To further investigate the welfare effects of the diverse treatments, it is instructive to compare the surplus and net trades, and the actual welfare with the predicted levels. In typical double auction settings (e.g., Ketcham et al., 1984; Friedman, 1984; Smith, 1962), high efficiency rates are observed.

The reduction of the externality is traded off against reductions in surplus as reported in Table 7 and illustrated in Fig. 6. As such, the treatment effects on efficiency are less promising: under a linear externality, we do not find any positive treatment effect on the efficiency level (see Table A.7). Under the exponential externality, however, both *locational* ($pval = 0.05$, Mann-Whitney U test) and full *internalization* ($pval = 0.015$, Mann-Whitney U test) have a positive effect on welfare relative to the corresponding *baseline* treatment (see Table A.8).

The equilibrium prediction in our *baseline* treatment involves a surplus of 184, with four net trades occurring and leading to welfare level of 144 in the linear and 134 in the exponential externality variant. The realized trade surplus reaches 99% of the predicted values in the *baseline* treatment under both externality variants. Overall, the blind market in the *baseline* treatment thus confirms previous findings that double auctions generate a high efficiency close to equilibrium predictions.

However, the existence of the externalities obviously leaves room for beneficial interventions as the optimal welfare is 168 in the linear and 171 in the exponential externality variant. As there is no price differentiation in the *baseline* treatment the efficiency[18] only reaches 86% (linear) and 77% (exponential). While the *internalization* treatments perform better with regards to efficiency, the $internalization_L/internalization_E$ treatments realize “only” 87%/88% and thus cannot fully generate the predicted welfare gains. As the net trades (see Table 7) lead to only minor damages resulting from the externality, the missing welfare is largely due to not achieving the predicted surplus in the *internalization* treatment.

In order to explore this in more detail, we consider the likelihood that any individual unit is traded. Tables A.13 to A.16 show these probabilities (in brackets) and also indicate which units should be traded under the equilibrium predictions (shaded entries).

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[18] calculated as the realized welfare divided by the corresponding maximum reachable welfare.

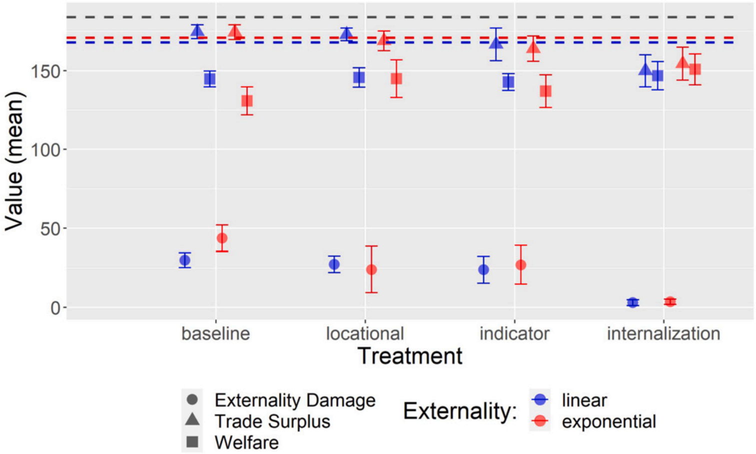

Fig. 6. Overview over mean surplus, externality damage and welfare. Observations are pooled over all rounds on the group level. Errorbars show 95% confidence intervals. The dotted lines indicate predicted trade surplus in the blind market and the surplus in the social optimum (red and blue). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

Table 8
Share of final accepted offers that were offers posted by sellers.

Treatment	Share of Sellers' Offers	pval Chi-squ H0: Share = 0.5
baseline_L	0.50	1
locational_L	0.72	0.000
indicator_L	0.47	0.617
internalization_L	0.55	0.453
baseline_E	0.56	0.317
locational_E	0.69	0.003
indicator_E	0.42	0.211
internalization_E	0.58	0.211

Comparing the *baseline* treatments (Tables A.13 and A.14) with the *internalization* treatments (Tables A.15 and A.16) suggests that the separation of units that should vs. should not be traded is less pronounced in the latter. For example, the marginal seller in A and the marginal buyer in B that just should *not* trade have probabilities of trading of 11% (22%) and 17% (19%) in the *baseline* treatment under linear (exponential) externality as seen in Tables A.13 and A.14. The corresponding probabilities under *internalization* are given by 44% (36%) and 33% (30%) and thus are substantially higher, see Tables A.15 and A.16. This suggests that the likelihood of wrong matches between buyers and sellers, i.e. units that should not be traded, are more frequent under the *internalization* treatment. One potential reason is the sequential nature of trades which leads to some trades being taxed, while others are subsidized which may make such wrong matches overly attractive.

In the same line, we investigate variation in selling pressure. One possible effect of the externality and how it is integrated in the market is that it could put more pressure on one specific type of trader. Table 8 shows the share of accepted final offers that were posted by sellers.[19] The share is significantly different from 50% for the *locational* treatments ($pvals < 0.01$, (L&E), Chi-square test), independent of the form of the externality. This indicates that in this treatment sellers may perceive a higher pressure to sell their goods.[20] This increased pressure is mitigated by additional information (*indicator*-treatment) and pricing in of the externality (*internalization*-treatment).

5.3. Convergence over time

Due to the sequential nature of the double auction market, it is of interest how the different treatments influence the speed and level of convergence. Differences in the speed of convergence can be a potential reason for the treatment differences, especially with regards to welfare and efficiency. In the following we investigate convergence and time effects in two different ways: first, we discuss how the main variables (price differential, net trades, welfare) develop over the eight rounds. Second, we consider the evolution of within-round-variance of accepted offers, i.e. the variance of prices at which the units are traded within periods.

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[19] This approach to investigate selling pressure, can be found in similar literature, see e.g. Attanasi et al. (2021).

[20] We can only speculate on the mechanism for the increase in seller pressure: perhaps sellers try to attenuate the responsibility for triggering the externality as they do not know the location of the eventual buyer and, thus, if an externality is triggered or not. The effect on sellers may differ from the one for sellers due to some perceived social norms of buyers/consumers holding responsibility for the externality.

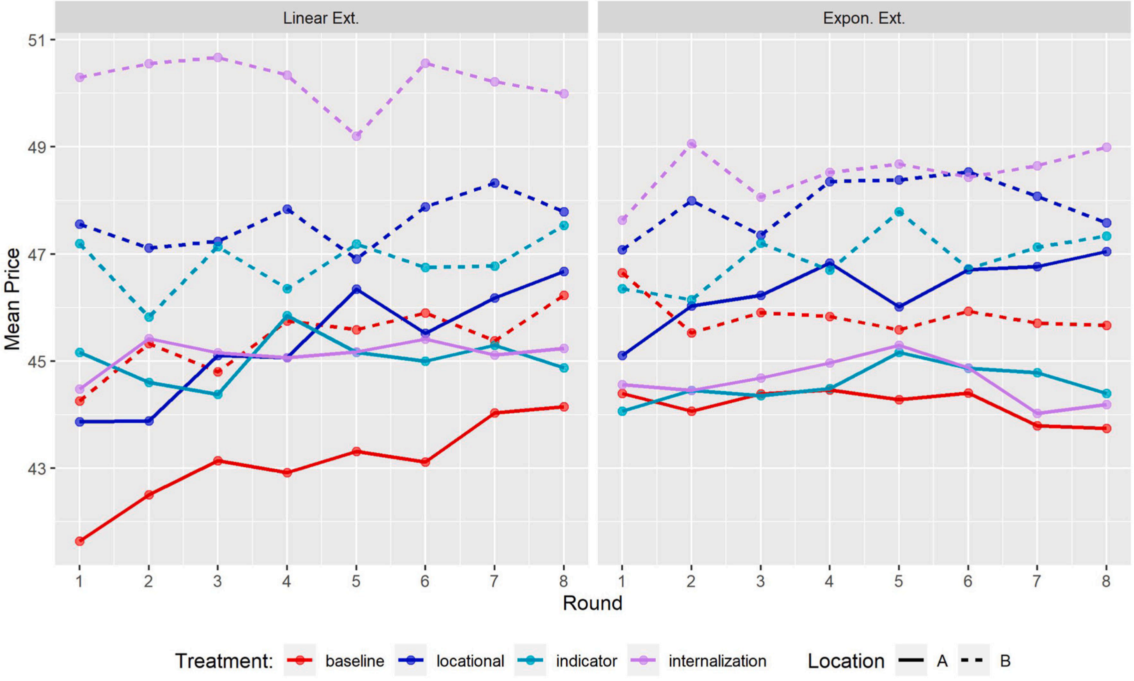

Fig. 7. Overall average price for each round/treatment, separated by location.

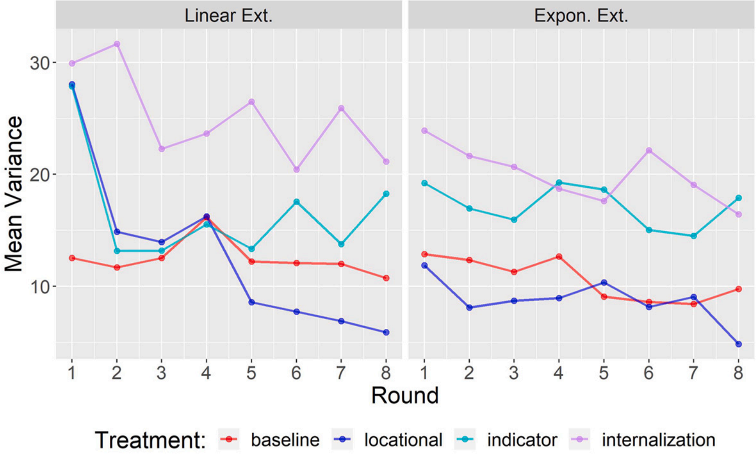

Fig. 8. Variances of accepted prices for each round/treatment. Variances are calculated within each group and round. Points display average over group variances.

We depict the price trends over the eight rounds in Fig. 7. With the linear externality, with the exception of the *internalization* treatments prices show a slight upwards trend over time. However, these trends are not significant as seen in Table A.17. With the exponential externality, prices are overall stable after round one. Table A.17 indicates no significant price trend in any of the treatments.[21] Regarding the price separation between locations, prices separate after round 1 and show a stable separation afterwards. In fact, the panel effects regressions in Table A.18 suggest a slight (yet significant) reduction of the price differential over time under the linear externality. Table A.19 reports the corresponding panel effects regressions on the number of net trades. Across all treatments, there is an increase in net trades over time, thus leading to larger externalities. Importantly, the *internalization* treatment breaks this positive trend and leads to stable net trades across periods, i.e. its time trend is significantly different from the *baseline* under linear externalities and *locational* and *indicator* treatments under exponential externalities. Welfare shows a positive trend over time, but the effect is not significant when round/treatment interactions are considered in the model, see Table A.20.

Fig. 8 displays the evolution of the variance of accepted offers over the eight rounds played under one externality variant. Fig. 9 additionally separates the variance by location. In general, we observe a steep drop in variance in the earlier rounds, especially after

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[21] The combined coefficients of round and round*indicator/round*internalization are not significantly different from 0 (pval round + round*indicator = 0: 0.24, pval round + round*internalization = 0: 0.37.

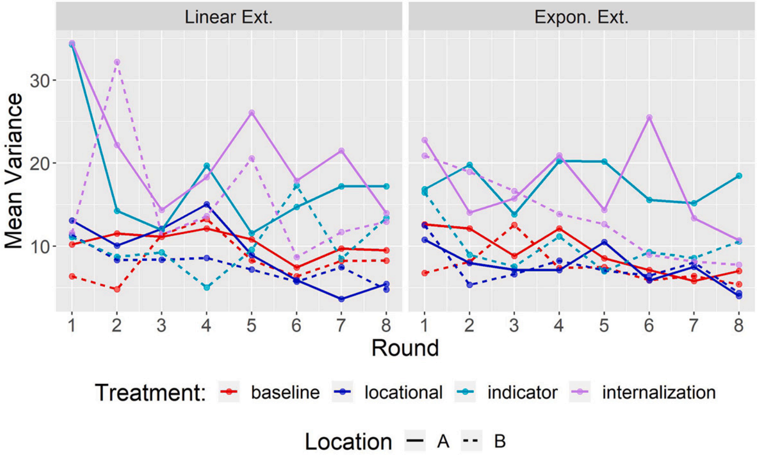

Fig. 9. Variances of accepted prices for each round/treatment with additional separation by location. Variances are calculated within each group and round. Points display average over group variances.

round one. This is in line with the behavior typically observed in double auction experiments as individuals learn about trading prices over time. However, while all treatments continue to show a downward trend, the *internalization* treatments show persisting higher terminal variances than the *baseline* and *locational* treatments (Wilcoxon rank sum test using only observations from rounds 5–8, $pvals < 0.05$, (L&E).[22] That is, once market participants know about the contribution of the next trade to the externality, i.e. both the level as well as the direction, the prices at which the trades are concluded show a larger variance. This is consistent with traders incorporating the varying externality levels into their bids and asks. We note that this is not possible in the *baseline* and *locational* treatments as market participants there are not informed about the current net trade situation.

Overall, we find convergence is similar between the treatments, but the variance is larger for treatments with stronger price separation (*internalization* & *indicator*). The same holds true for within location variance, so it is not explained by price separation by the price separation itself. This points towards the decrease of externalities in these treatments coming at a price of slower convergence and the efficiency losses associated with it.

6. Conclusion

This paper studies ways to deal with externalities that depend on the specific match between buyers and sellers in the marketplace. While our experimental design is inspired by electricity markets, match-dependent externalities can also occur in transportation settings.

We employ a modified double auction platform to incorporate locational information into the market design. Our baseline treatment is inspired by typical market platforms that are location-blind and thus do not give market participants the information on externality-relevant characteristics of potential trading partners. In line with previous literature on double auction settings, the behavior is close to equilibrium predictions. Yet, in our setting this leaves substantial room for welfare improvements as the externality is not incorporated into individual decision making.

We demonstrate that locational information is sufficient to reduce the externality. Imposing the full external costs on individual trades leads to maximal price differentiation between locations and further reduces net trades. While the externality is thus countered, the welfare gains do not fully materialize.

Our data reveals two potential reasons for lacking efficiency gains: First, the internalizing of the externality leads to more extra-marginal trades. Second, the convergence of the market is reduced under internalization, thus leading to a larger variance of prices and trades and thereby affecting overall efficiency. It remains an open question whether the convergence differences persist over time and if they depend on the sequentiality of trades which lets the external costs imposed on the individual trades vary with the current level of congestion/net trade.

Our paper adds to the literature on externalities arising in market settings. Most of this literature is concerned with externalities triggered through consumption, production, or trade. The role of externalities arising from the specific match between trading partners has largely been overlooked. Our experimental evidence provides first guidance to designing market platforms to deal with such match-dependent externalities. Further research is needed into the exact mechanisms that prevent welfare gains even under internalization. Another direction in which our research can be expanded is the interplay of match-dependent externalities and market power.

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[22] For the exact test results, see Tables A.9–A.12 in the Appendix.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Johannes Ross reports financial support was provided by German Federal Ministry for Economic Affairs and Energy. Andreas Lange reports financial support was provided by German Federal Ministry for Economic Affairs and Energy.

Data availability

Data will be made available on request.

Appendix A

Table A.1
Wilcoxon rank sum test pvals for difference in net-trades between treatments for linear externality.

Net-trades	lin *baseline*	lin *locational*	lin *indicator*	lin *internalization*
lin baseline	na	–	–	–
lin *locational*	0.874	na	–	–
lin *indicator*	0.317	0.399	na	–
lin *internalization*	0.001	0.001	0.004	na

Table A.2
Wilcoxon rank sum test pvals for difference between net-trades between treatments for exponential externality.

Net-trades	exp *baseline*	exp *locational*	exp *indicator*	exp *internalization*
exp baseline	na	–	–	–
exp *locational*	0.004	na	–	–
exp *indicator*	0.074	0.712	na	–
exp *internalization*	0.003	0.001	0.0059	na

Table A.3
Wilcoxon rank sum test pvals for difference in trades from location A to location B between treatments for linear externality.

Trades A to B	lin *baseline*	lin *locational*	lin *indicator*	lin *internalization*
lin baseline	na	–	–	–
lin *locational*	0.052	na	–	–
lin *indicator*	0.058	0.460	na	–
lin *internalization*	0.001	0.005	0.007	na

Table A.4
Wilcoxon rank sum test pvals for difference in trades from location A to location B between treatments for exponential externality.

Trades A to B	exp *baseline*	exp *locational*	exp *indicator*	exp *internalization*
exp baseline	na	–	–	–
exp *locational*	0.035	na	–	–
exp *indicator*	0.051	0.494	na	–
exp *internalization*	0.001	0.005	0.002	na

Table A.5
Wilcoxon rank sum test pvals for difference in trades from location B to location A between treatments for linear externality.

Trades B to A	lin *baseline*	lin *locational*	lin *indicator*	lin *internalization*
lin baseline	na	–	–	–
lin *locational*	0.023	na	–	–
lin *indicator*	0.187	0.874	na	–
lin *internalization*	0.021	0.171	0.291	na

Table A.6
Wilcoxon rank sum test pvals for difference in trades from location B to location A between treatments for exponential externality.

Trades B to A	exp *baseline*	exp *locational*	exp *indicator*	exp *internalization*
exp baseline	na	–	–	–
exp *locational*	0.494	na	–	–
exp *indicator*	0.673	0.527	na	–
exp *internalization*	0.315	0.710	0.223	na

Table A.7
Wilcoxon rank sum test pvals for difference in welfare between treatments for linear externality.

Efficiency	lin *baseline*	lin *locational*	lin *indicator*	lin *internalization*
lin baseline	na	–	–	–
lin *locational*	0.793	na	–	–
lin *indicator*	0.599	0.645	na	–
lin *internalization*	1	1	0.563	na

Table A.8
Wilcoxon rank sum test pvals for difference in welfare between treatments for exponential externality.

Efficiency	exp *baseline*	exp *locational*	exp *indicator*	exp *internalization*
exp baseline	na	–	–	–
exp *locational*	0.050	na	–	–
exp *indicator*	0.599	0.318	na	–
exp *internalization*	0.015	0.207	0.066	na

Table A.9
Wilcoxon rank sum test pvals for difference in variance between treatments for linear externality. Only observations from rounds 5–8 are used.

Variance	lin *baseline*	lin *locational*	lin *indicator*	lin *internalization*
lin baseline	na	–	–	–
lin *locational*	0.234	na	–	–
lin *indicator*	0.798	0.195	na	–
lin *internalization*	0.0281	0.003	0.195	na

Table A.10
Wilcoxon rank sum test pvals for difference in variance between treatments for exponential externality. Only observations from rounds 5–8 are used.

Variance	exp *baseline*	exp *locational*	exp *indicator*	exp *internalization*
exp baseline	na	–	–	–
exp *locational*	1	na	–	–
exp *indicator*	0.382	0.160	na	–
exp *internalization*	0.038	0.028	0.574	na

Table A.11
Wilcoxon rank sum test pvals for difference in variance between treatments for linear externality. Only observations from rounds 5–8 are used. Variances are calculated within each location.

Variance	lin *baseline*	lin *locational*	lin *indicator*	lin *internalization*
lin baseline	na	–	–	–
lin *locational*	0.328	na	–	–
lin *indicator*	0.959	0.328	na	–
lin *internalization*	0.234	0.028	0.442	na

Table A.12
Wilcoxon rank sum test pvals for difference in variance between treatments for exponential externality. Only observations from rounds 5–8 are used. Variances are calculated within each location.

Variance	exp *baseline*	exp *locational*	exp *indicator*	exp *internalization*
exp baseline	na	–	–	–
exp *locational*	0.798	na	–	–
exp *indicator*	0.382	0.130	na	–
exp *internalization*	0.160	<0.050	0.849	na

Table A.13
Valuations/Costs in the *baseline* treatment; linear externality; numbers in brackets indicate the probability that the corresponding unit is traded, calculated from the experimental data; shaded units are traded in equilibrium.

	Location							
	A				B			
Unit	S1	S2	B1	B2	S1	S2	B1	B2
1	31(1.00)	33(1.00)	55(0.97)	53(0.98)	39(0.95)	41(0.97)	63(0.97)	61(1.00)
2	35(1.00)	37(1.00)	51(0.95)	49(0.95)	43(0.86)	45(0.92)	59(0.95)	57(0.98)
3	39(0.98)	41(0.97)	47(0.77)	45(0.36)	47(0.63)	49(0.17)	55(0.84)	53(0.94)
4	43(0.88)	45(0.72)	43(0.08)	41(0.00)	51(0.05)	53(0.00)	51(0.77)	49(0.72)
5	47(0.41)	49(0.11)	39(0.00)	37(0.00)	55(0.00)	57(0.00)	47(0.22)	45(0.17)

Table A.14
Valuations/Costs in the *baseline* treatment; exponential externality; numbers in brackets indicate the probability that the corresponding unit is traded, calculated from the experimental data; shaded units are traded in equilibrium.

	Location							
	A				B			
Unit	S1	S2	B1	B2	S1	S2	B1	B2
1	31(0.98)	33(1.00)	55(0.94)	53(0.94)	39(1.00)	41(0.97)	63(1.00)	61(1.00)
2	35(0.97)	37(1.00)	51(0.87)	49(0.84)	43(0.92)	45(0.83)	59(1.00)	57(1.00)
3	39(0.94)	41(0.98)	47(0.66)	45(0.23)	47(0.52)	49(0.20)	55(0.95)	53(0.91)
4	43(0.78)	45(0.89)	43(0.05)	41(0.02)	51(0.02)	53(0.00)	51(0.75)	49(0.69)
5	47(0.33)	49(0.22)	39(0.00)	37(0.00)	55(0.00)	57(0.00)	47(0.44)	45(0.19)

Table A.15
Valuations/Costs in the *internalization* treatment; linear externality; numbers in brackets indicate the probability that the corresponding unit is traded, calculated from the experimental data; shaded units are traded in equilibrium.

	Location							
	A				B			
Unit	S1	S2	B1	B2	S1	S2	B1	B2
1	31(0.81)	33(0.94)	55(0.97)	53(0.97)	39(1.00)	41(0.95)	63(0.98)	61(0.98)
2	35(0.77)	37(0.91)	51(0.95)	49(0.92)	43(0.97)	45(0.90)	59(0.86)	57(0.95)
3	39(0.72)	41(0.88)	47(0.73)	45(0.70)	47(0.81)	49(0.73)	55(0.75)	53(0.88)
4	43(0.45)	45(0.44)	43(0.38)	41(0.28)	51(0.36)	53(0.14)	51(0.38)	49(0.33)
5	47(0.17)	49(0.13)	39(0.05)	37(0.00)	55(0.03)	57(0.00)	47(0.02)	45(0.03)

Table A.16
Valuations/Costs in the *internalization* treatment; exponential externality; numbers in brackets indicate the probability that the corresponding unit is traded, calculated from the experimental data; shaded units are traded in equilibrium.

	Location							
	A				B			
Unit	S1	S2	B1	B2	S1	S2	B1	B2
1	31(1.00)	33(0.84)	55(0.92)	53(0.95)	39(1.00)	41(0.97)	63(0.98)	61(0.97)
2	35(0.97)	37(0.81)	51(0.89)	49(0.92)	43(0.95)	45(0.92)	59(0.95)	57(0.86)
3	39(0.91)	41(0.61)	47(0.81)	45(0.73)	47(0.75)	49(0.70)	55(0.83)	53(0.64)
4	43(0.59)	45(0.36)	43(0.41)	41(0.17)	51(0.23)	53(0.16)	51(0.69)	49(0.30)
5	47(0.20)	49(0.17)	39(0.02)	37(0.00)	55(0.02)	57(0.06)	47(0.14)	45(0.05)

Table A.17
Random effects estimation with last accepted price as dependent variable. Standard errors in parentheses. Rounds are noted as 1–8.

	Price (last accepted)			
	Linear		Exponential	
locational	−0.36	−0.50	0.81	1.59
	(0.95)	(1.42)	(0.82)	(1.16)
indicator	−0.58	−0.85	0.44	2.07^{*}
	(0.95)	(1.42)	(0.82)	(1.16)
internalization	0.36	1.36	-1.80^{**}	−0.33
	(0.95)	(1.42)	(0.82)	(1.16)
round	0.03	0.07	−0.01	0.21
	(0.08)	(0.17)	(0.06)	(0.13)
round**locational*		0.03		−0.17
		(0.23)		(0.18)
round**indicator*		0.06		-0.36^{**}
		(0.23)		(0.18)
round**internalization*		−0.22		-0.33^{*}
		(0.23)		(0.18)
Constant	46.91^{***}	46.77^{***}	46.60^{***}	45.63^{***}
	(0.77)	(1.01)	(0.65)	(0.82)
Observations	256	256	256	256
R^2	0.01	0.01	0.05	0.06
Adjusted R^2	−0.01	−0.02	0.03	0.04

Note: $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$.

Table A.18
Random effects estimation with price spread as dependent variable. Standard errors in parentheses. Rounds are noted as 1–8.

	Price Spread			
	Linear		Exponential	
locational	1.17	2.24^{*}	1.05	0.76
	(0.95)	(1.35)	(0.92)	(1.20)
indicator	1.39	2.55^{*}	1.20	−0.14
	(0.95)	(1.35)	(0.92)	(1.20)
internalization	5.47^{***}	5.75^{***}	3.92^{***}	3.69^{***}
	(0.95)	(1.35)	(0.92)	(1.20)
round	-0.24^{***}	−0.10	0.02	−0.09
	(0.07)	(0.15)	(0.06)	(0.12)
round**locational*		−0.24		0.06
		(0.21)		(0.17)
round**indicator*		−0.26		0.30^{*}
		(0.21)		(0.17)
round**internalization*		−0.06		0.05
		(0.21)		(0.17)
Constant	1.62^{**}	1.00	0.35	0.82
	(0.76)	(0.96)	(0.71)	(0.85)
Observations	511	511	512	512
R^2	0.09	0.09	0.04	0.04
Adjusted R^2	0.08	0.08	0.03	0.03

Note: $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$.

Table A.19
Random effects estimation with net trades as dependent variable. Standard errors in parentheses. Rounds are noted as 1–8.

	Net trades			
	Linear		Exponential	
locational	−0.58	−0.70	−1.13***	−2.18***
	(0.40)	(0.47)	(0.42)	(0.50)
indicator	−0.61	−0.54	−0.83**	−1.89***
	(0.40)	(0.47)	(0.42)	(0.50)
internalization	−2.43***	−1.90***	−2.27***	−2.44***
	(0.40)	(0.47)	(0.42)	(0.50)
round	0.08***	0.10***	0.06**	−0.07
	(0.02)	(0.04)	(0.02)	(0.04)
round**locational*		0.03		0.23***
		(0.06)		(0.06)
round**indicator*		−0.01		0.24***
		(0.06)		(0.06)
round**internalization*		−0.12**		0.04
		(0.06)		(0.06)
Constant	2.35***	2.23***	2.67***	3.24***
	(0.30)	(0.34)	(0.31)	(0.36)
Observations	511	511	512	512
R^2	0.10	0.11	0.07	0.11
Adjusted R^2	0.09	0.10	0.06	0.10

Note: *p<0.1; **p<0.05; ***p<0.01.

Table A.20
Random Effects Estimation with final welfare as dependent variable. Standard errors in parentheses. Rounds are noted as 1–8.

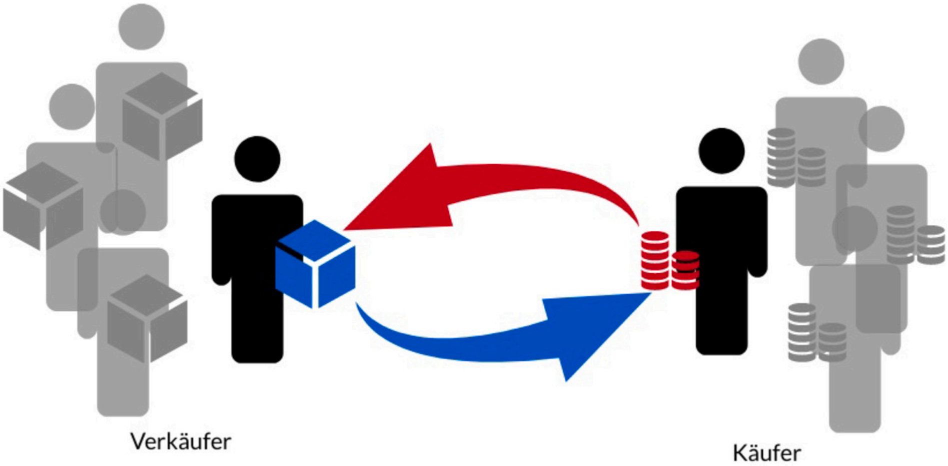
	Welfare			
	Linear		Exponential	
locational	0.97	−2.21	14.14**	14.72
	(4.47)	(6.57)	(7.04)	(9.84)
indicator	−1.94	−0.41	6.20	12.12
	(4.47)	(6.57)	(7.04)	(9.84)
internalization	2.03	−5.21	20.11***	19.67**
	(4.47)	(6.57)	(7.04)	(9.84)
round	1.66***	1.16	1.48***	1.81*
	(0.38)	(0.75)	(0.54)	(1.07)
round**locational*		0.71		−0.13
		(1.07)		(1.52)
round**indicator*		−0.34		−1.31
		(1.07)		(1.52)
round**internalization*		1.61		0.10
		(1.07)		(1.52)
Constant	137.32***	139.54***	124.18***	122.67***
	(3.59)	(4.65)	(5.53)	(6.96)
Observations	256	256	256	256
R^2	0.18	0.20	0.10	0.12

Note: *p<0.1; **p<0.05; ***p<0.01.

Appendix B. Instructions internalization treatment (translated from German)

Thank you for participating in this economic experiment. Please read these instructions carefully, you will have to answer test questions later. The instructions are identical for all participants. Your payout will depend on both yours' and other participants' behavior. You will be paid after the experiment.

In this experiment, you participate in a market where you are either a buyer or a seller. The currency on the market is not Euros, but ECU. Sellers own goods that they can sell to buyers for ECU.



In addition, buyers and sellers are in different locations, which can lead to costs. Once the experiment starts, you will see on your screen if you are a buyer or a seller, what location you are in, and a custom table that shows the value each purchase/sale has to you. Only you have this information; no other participant knows your table.

Buyers:

Buyers can acquire a maximum of five units of the good from any number of sellers in each market period. Each unit results in a different payout for them. The example table shows that the first unit purchased has a value of 50 ECU, the second unit 40, and so on (note that you will get a different table in the experiment). In addition, you will receive a commission of 0.5 ECU for every purchase.

Payout Table (Example)	
Unit	Payout (in ECU)
1	50
2	40
3	30
4	20
5	10

The profit from each purchase is calculated from the payout minus the price paid plus the commission:

$$\text{Profit} = (\text{Payout})\text{-}(\text{Price}) + (\text{Commission})$$

For example, if you bought one unit for 30 ECU and one unit for 25 ECU (using the table above), your profit is as follows (including the 0.5 ECU commission per purchase):

Profit Unit 1:	$= 50 - 30 + 0.5$	$= 20.5$
Profit Unit 2:	$= 40 - 25 + 0.5$	$= 15.5$
Total Profit:	$= 20.5 + 15.5$	$= 36$

Sellers:

Sellers can sell a maximum of five units of the good in each market period. Each unit sold results in different costs for them. The example table shows that the first unit sold has a cost of 10 ECU, the second unit has a cost of 20 ECU, and so on (note that you will get a different table later in the experiment). In addition, you will receive a commission of 0.5 ECU for every sale.

Your profit from each sale is calculated as the price received minus the cost of the unit plus the commission.

$$\text{Profit} = (\text{Price})\text{-}(\text{Costs}) + (\text{Commission})$$

For example, if you sold one unit for 35 ECU and one unit for 40 ECU, your profit is as follows (including the 0.5 ECU commission per sale):

Cost Table (Example)

Unit	Costs (in ECU)
1	10
2	20
3	30
4	40
5	50

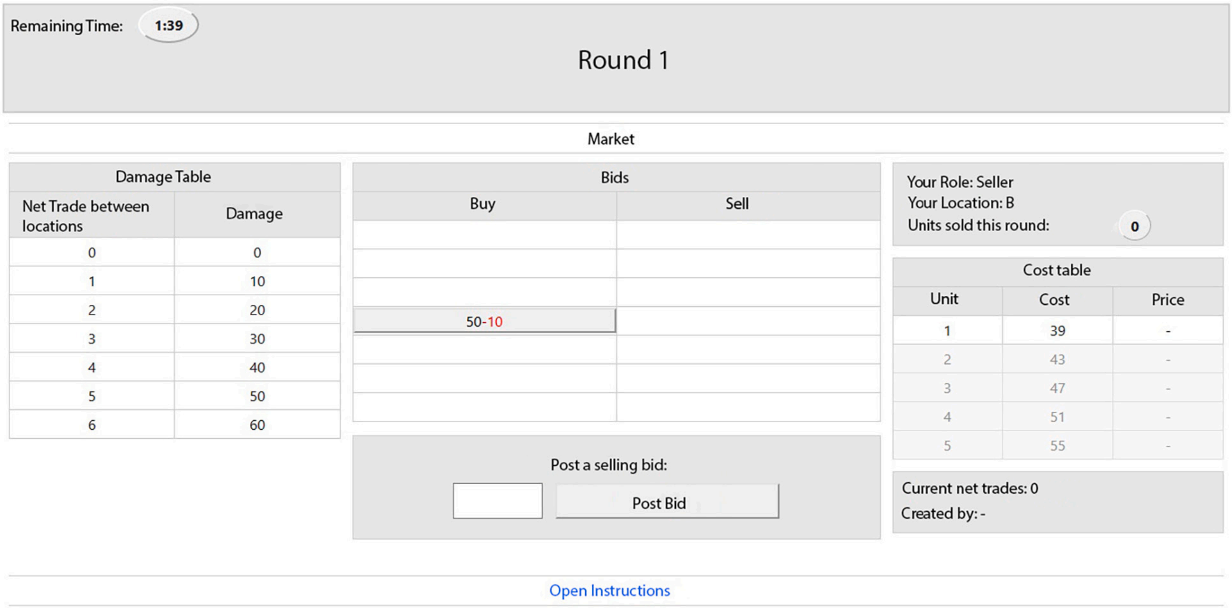
Profit Unit 1: $= 35 - 10 + 0.5$ $= 25.5$

Profit Unit 2: $= 40 - 20 + 0.5$ $= 20.5$

Total Profit: $= 25.5 + 20.5$ $= 46$

Market:

The market where you can buy/sell is made up of 4 buyers and 4 sellers. It is organized as follows: The market stays open for 2 minutes each round. A corresponding timer is displayed. As long as the market is open, buyers can bid and sellers can bid. A purchase bid indicates the willingness to pay the bid amount for a unit of the good. A sell bid indicates the willingness to sell a unit for the amount offered. Buyers can accept a bid to sell at any time and sellers can accept a bid to buy at any time. To accept a bid, simply click on the relevant bid. No bids can be submitted or accepted in which participants would lose money. All bids are visible to all participants at all times. Below is a screenshot of the market surface:



Remaining Time: 1:39

Round 1

Market

Damage Table

Net Trade between locations	Damage
0	0
1	10
2	20
3	30
4	40
5	50
6	60

Bids

Buy	Sell
50-10	

Your Role: Seller
Your Location: B
Units sold this round: 0

Cost table

Unit	Cost	Price
1	39	-
2	43	-
3	47	-
4	51	-
5	55	-

Current net trades: 0
Created by: -

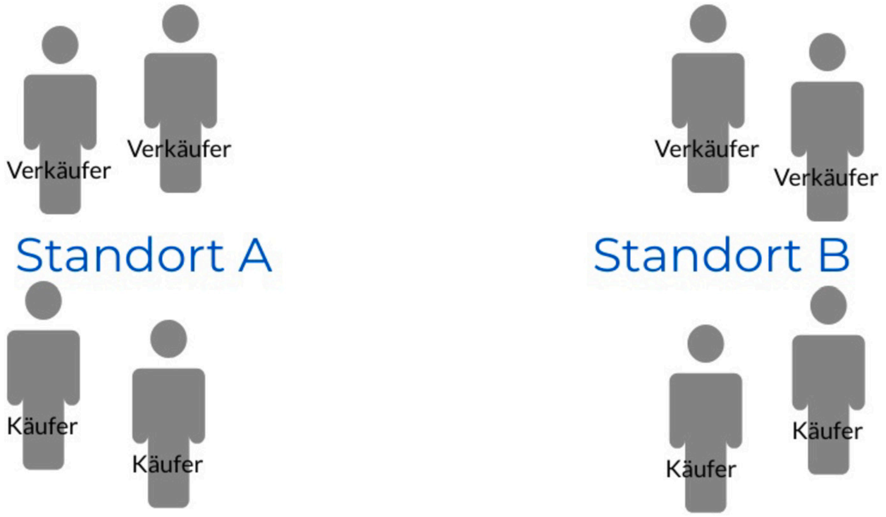
In addition to the amount of the bid, the location from which the bid comes is displayed. This is relevant for the development of potential damage. In addition, you will be informed about the current trade balance between the two locations A and B, and what damage is currently arising from it. Every bid on the market is adjusted so that it already includes the resulting damage or damage avoidance. The amount of this damage or the damage avoidance is displayed next to the bids that have been made. The occurrence of damage is explained in detail below.

If a bid is accepted, the offered/requested unit is transferred at the corresponding price. All bids will then be deleted and new bids can be submitted. Even if your bid is not accepted, you can keep trying to trade and make as much profit as possible.

If the time runs out, the trading period ends. All profits are realized and all units of the good are reset. Then a new round begins. There will be a total of 16 rounds.

Location

There are always 4 buyers and 4 sellers. Each participant is either in location A or in location B. In each location there are 2 buyers and 2 sellers. A trader's location does not change during the experiment.



Damages

At the end of each round you will receive a bonus of 10 ECU. However, trade can cause damage if it is unbalanced between different locations.

Damage is only caused by net trade between locations. Trading within a location (e.g. between a buyer and a seller in location A) never leads to damage. Trade between locations (e.g. between a buyer in location A and a seller in location B) can cause damage. However, this only happens when trade in one direction predominates. If a unit is sold from location A to location B and a unit from location B to location A, no damage results.

The amount of the total damage depending on the net trade is shown in a table. You can see an example table here:

Damage Table	
Net-Trade between Locations	Damage (in ECU)
0	0
1	10
2	20
3	40
4	70
5	80

Examples:

- Upon end of the round, the following trades have occurred: 4 trades within location A, 3 trades within location B. Since there is no trade between A and B, no damage has occurred.
- If there have been 4 trades from A to B and 2 trades from B to A, the net trade between locations is 2. This results in a damage of 20.
- If there have been 5 trades from B to A and 1 trade from A to B, the net trade between locations is 4. This results in a damage of 70.

Test Questions:

1. Suppose you are a buyer with the following payout table:

Payout Table (Example)	
Unit	Payout
1	80
2	60
3	30
4	20
5	10

   You have acquired a total of 3 units in one round. How high is your total payout (regardless of the prices paid)? (170)
2. You paid a price of 40, 60 and 30 for units 1, 2 and 3. What is your profit this round? Note the commission per purchase. (170 - 130 + 1.5 = 41.5)

3. Suppose you are a seller with the following cost table:

Cost Table (Example)	
Unit	Costs
1	20
2	30
3	30
4	40
5	60

You have sold a total of 3 units in one round. What are your total costs (regardless of the prices paid)? (80)

4. You received a price of 40, 60 and 30 for units 1, 2 and 3. What are your profit this round? Note the commission per purchase. (130 -80 + 1.5 = 51.5)
5. The following damage table is given.

Damage Table	
Net-Trade between Locations	Damage
0	0
1	10
2	20
3	40
4	70
5	80

What is the total damage if there are 5 trades from A to B and 3 trades from B to A? (20)

6. At the end of a round there is a damage of 20. What is the portion that is deducted from you? (0)

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